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* FINAL REPORT:
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* TIMESHARING PERFORMANCE
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* AS AN
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* INDICATOR OF PILOT MENTAL WORKLOAD *

Prepared by

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I. Summary of completed research (1/1/85 - 12/31/86)

The sponsored research was carried out in two simultaneous phases, each intended to identify and manipulate factors related to operator mental workload. The first phase concerned evaluation of attentional deficits (workload) in a timesharing task developed at the human information processing laboratory at Purdue. Work in the second phase involved incorporating the results from these and other experiments into an expert system designed to provide workload metric selection advice to non-experts in the field interested in operator workload. For the most part, the results of the experiments conducted are summarized in general, with the details available in the papers found in the Appendices.

Two years of research at Purdue and at NASA-Ames were successful in identifying some of the salient factors associated with operator mental workload in complex task situations. In the laboratory at Purdue, a series of experiments using a bimodal (auditory and visual) divided attention task has revealed that operators are not limited in their ability to attend to simultaneous events - the limitations arise when they are required to make responses to them. Cross-sectioned slices of the task's data at different points in time showed that performance in one modality is not affected by perceptual events in the other modality, such as changes in color of a display, for example. Performance on the task in one modality suffered the most when something occurred in the other modality that required a response, such as the flash of a light that had special significance to the operator (Casper, 1986; Kantowitz & Casper, in press).

The ratio of sub-tasks also appears to be an important factor affecting workload. According to previous research supported by Gestalt principles of perception, (Klapp, Hill, and Tyler, 1983), tasks in which the ratio of visual to auditory events is a harmonic one (e.g. 1:1, 2:1) should be easier than tasks in which there is a "non-harmonic" ratio between the stimuli (e.g. 3:2). Our research, based on attention theory, found the opposite to be true -- tasks having a 3:2 ratio of visual to auditory stimuli are in fact easier to perform than tasks in which the auditory and visual events occur simultaneously (Casper & Kantowitz, 1985). In some respect this advantage was due to the fact that there was more asynchrony of processing demands between the two tasks in the 3:2 case. This hypothesis is supported by the results of an experiment in which there was some advantage when two tasks of the same ratio were presented with one task lagging slightly behind the other.

The second phase of the research focused on the transfer of workload knowledge obtained from empirical studies to the practitioner responsible for making workload-related decisions.

With the ever-increasing concern for issues of safety, efficiency, and enhanced performance in aviation, more and more people are becoming interested in pilot workload. However, not all those interested in workload have adequate knowledge about it to know how to begin evaluation. Recent advances in the field of artificial intelligence have made several expert system development tools available to those who wish to build expert or decision support systems but who haven't the programming knowledge (or money) themselves to create it from scratch. In essence, the tools are "expert systems for building expert systems".

During the summer of 1986, one of these tools was used to create a microprocessor-based prototype of a system that makes recommendations concerning the choice of workload metrics, depending on the user's research goals, available equipment, and task environment (Casper, Shively, & Hart, 1986). After asking the user a series of questions related to these factors, the thirteen workload metrics are ordered with respect to their appropriateness for the user's situation. Metrics that are completely inappropriate for the user are not suggested at all, while more appropriate measures are offered with a number from 1 to 10 indicating the degree to which they would be helpful to the user. Following the suggestions, the program allows the user to access workload information files where he may learn more about any of the measures included in the database. The files represent the most current available information concerning a measure's empirical success, its practical limitations, and its advantages and disadvantages. These files may be viewed on the computer screen or routed to a printer to obtain a hard copy.

II. Summary of completed research during extension (1/1/87 - 5/31/88)

A. Laboratory research at Purdue

The research conducted at Purdue during the final year of the project addressed two questions:

- 1) Is heart rate variability a valid indicator of overall operator mental workload in our laboratory task?
- 2) If it is, can it be used to provide further insight on the location of bottlenecks in the human information processing system?

In general, three broad classes of measures have been used to assess operator workload: subjective, performance, and physiological. Not surprisingly, each class of measures (and even measures within classes) have their unique advantages and disadvantages. Unlike the first two classes of measures, the physiological indices of workload have a distinct advantage in that they are unobtrusive to the operator performing a task.

Although not as crucial a factor in the laboratory it is obvious why unobtrusiveness would be advantageous in an operational situation such as a low-altitude helicopter mission, for example.

Much research has been done supporting the use of various computations of heart rate variability as an indicator of operator workload, ranging from the standard deviation of the variability of the interval between successive heart beats to a more complicated analysis of the power in different spectral bands of the heart beat signal. A review of the current literature has raised several issues, namely, the problem of contamination of overall heart rate variability with influences from factors other than mental load, how to reconcile conflicting results obtained from different computations of variability, and the problem of how to interpret heart rate variability changes within the context of a given experimental design (Kalsbeek, 1973).

An experiment using the aforementioned divided attention task was conducted at Purdue in order to evaluate the sensitivity of cardiac measures of workload to manipulations of the difficulty of the task. Subjects simultaneously attended to two streams of discrete stimuli, and responded manually to changes in one modality and vocally to changes in the other modality. The events in the auditory modality were high or low-frequency tones and the visual events were flashes of a red or green light. Subjects were instructed to respond as quickly as possible via either a keypress or by saying the word "diff" into a microphone each time they observed a signal in a modality that was different from the previous signal in that modality. Half of the subjects used a vocal response to the auditory channel and a manual response to the visual channel, while for the other half of the subjects the response requirements were reversed. It should be noted that the response mappings for the former group should lead to better performance, since input and output modalities are more compatible for the auditory task than those used by the latter group (Wickens, 1980). Tasks employing multiple modalities are useful in that they parallel tasks in operational environments more than the traditional laboratory tasks, both in their difficulty and in their multimodal nature.

Task difficulty was manipulated by varying the number of tasks simultaneously performed (one = single stimulation, two = double stimulation) and the degree of synchrony between two tasks. In the synchronous case, the auditory and visual stimuli occurred simultaneously, and in the asynchronous case, presentation of the auditory or the visual sequence was delayed by 300 msec after that in the other modality. Presumably, tasks that occur asynchronously in each modality are easier to perform since attention may be switched between the two and responses need not necessarily be executed simultaneously. Due to equipment malfunctions heart rate (HR) data was available for only 6 of the 24 subjects run in the experiment. Mean HR scores showed that HR decreased throughout the experiment, presumably

indicating decreased arousal throughout the experiment. Of HR, HR variance, mean successive difference in IBI's (MSD), and variance of successive differences in IBI's, only mean HR reflected differences between the pre-task baseline period (82 beats per minute [BPM]) and the task period (76 BPM). HR did not distinguish between the single and double stimulation versions of the task.

HR variance was significantly greater during the last half of the experiment than in the first half, but decreased within a half, perhaps reflecting the fact that subjects were growing increasingly fatigued and exerting greater effort during the portions of the experiment between rest periods. The experiment lasted for an hour and a half. Spectral analysis of the IBI data did not reveal differential sensitivity of four different frequency bands to the manipulations of task difficulty.

The results of the performance measures are summarized in the paper appearing in the Appendix (Casper & Kantowitz, 1987).

There are a number of reasons why the cardiac measures were not sensitive to difficulty manipulations that have previously been successful as measured by performance. The first reason has to do with the motivational state of the subjects. The subjects used for the experiment were students in an introductory psychology class and received 1 1/2 hours of course credit simply for showing up for the experiment. No performance criteria were imposed on the subjects. It is possible that the task did not cause differing degrees of effort in the subjects. The task was purposely made difficult in order to elevate the level of missed responses and false alarms needed for the signal detection measure of performance. In addition, the subjects were not given explicit performance feedback. After a block of trials the experimenter simply told them whether or not they had achieved the 50% criterion necessary for remaining in the experiment. Other studies have demonstrated that feedback is an essential component in the operator-task loop. Second, it is possible that the requirement of a vocal response to one of the tasks forced the subjects to use an artificial breathing pattern in order to keep up with the regularly-paced task. Previous studies have shown that changes in breathing patterns are reflected in HR data, possibly obscuring the effects of other experimental factors. Further, it is entirely possible that the null results reflect insufficient power in the design, since 3/4 of the HR data was not available due to the equipment malfunction. However, one would at least expect a trend in the right direction.

If cardiac measures are to be successfully used in future timesharing experiments like those described above, some modifications to the task should be made. Vocal responses are probably to be avoided in tasks where breathing is likely to be entrained to a regular rhythm. Further, motivational incentives are likely to induce the subjects to invest a greater degree of

effort and involvement in the task. The subjects could be offered a cash prize for attaining a given score on the task, and frequent feedback could be used to inform the subject of his progress toward meeting those goals.

In addition to the methodological problems mentioned above, the study of cardiac correlates of cognition is sorely in need of some kind of theoretical framework from which empirical data can be predicted and interpreted. It is likely that progress toward such a goal will require that the concept of mental workload be viewed as a multidimensional construct, with different classes of measures tapping different dimensions of workload.

B. Expert system development at NASA-Ames and Purdue

The prototype of the system created during the summer of 1986 was extensively revised and tested using several different testing methods. Some of the workload measures from the original prototype were dropped, and some new ones were added, mostly a number of secondary tasks and rating scales. The questions asked of the user were also extensively revised; useless questions (those that did not warrant a distinction among workload measures) were dropped, and the wording on ambiguous questions was clarified. In addition, if secondary task measures were among the measures suggested to the user, potential input and output modalities for those tasks were determined.

One of several major problems currently facing the field of artificial intelligence is how to qualitatively and quantitatively evaluate the validity of the advice or information provided by intelligent decision aiding systems. No standard methods of testing exist, either across or within fields of application. Since WC FIELDE is potentially a very useful and attractive tool for many researchers, several attempts at mathematical validation have been made. Although the absolute utility of the advice WC FIELDE provides will ultimately be revealed by the user, several methods of assessing its overall and relative sensitivity have been devised.

The first evaluation was used to determine the baseline sensitivity of the system to the user's input. Random numbers were used as input to the system, on the assumption that if the probabilities associated with the rules had more influence on the results than the user's input then the output of the system would always be the same. If the system is truly sensitive to the answers the user supplies to the questions then the results should be different each time the system is run. The mean correlation among 20 random runs for version 1.0 of WC FIELDE was $r = .42$, and for version 2.0 it was $r = .16$. Thus, revisions to the system were effective in increasing the sensitivity of the system to the user's input.

A second sensitivity test was performed in which hypothetical users answered the questions posed by WC FIELDE as if they were the experimenter seeking workload advice for operators performing both easy and difficult tasks in two different environments. Ten subjects were asked to answer the questions for: 1) driving a car with a manual transmission in city traffic, 2) driving a car with a manual transmission on the freeway, 3) taking a calculus final, and 4) taking an introductory psychology final. No other information was given to the subjects. One group of ten subjects used version 1.0 of WC FIELDE, while another ten subjects used version 2.0. The correlation among the measures recommended by the program for all subjects using each of the four conditions was calculated.

The correlations among measures was higher within than between environments, suggesting that WC FIELDE was able to recommend different kinds of measures depending on the task environment or situation of the experimenter. In addition, the correlation within levels of difficulty was higher than between levels of difficulty for the final exam task in version 2.0, but for neither tasks in version 1.0. That is, the kinds of measures recommended for a situation in which the operator is performing an easy task are different from those suggested for when the operator is performing a more difficult task. The fact that WC FIELDE is able to make this distinction is significant, since one of the most important factors in determining which class of measures will be most sensitive to workload variations is the level of workload the operator is expected to withstand. Future testing of the system will employ more distinct difficulty and environment manipulations in order to allow the correlations to fully work out.

As WC FIELDE is revised, it will continue to be tested using the methods outlined above. In addition, several more novel testing methods have been suggested, which should provide converging evidence of the validity of ongoing revisions. The system is currently being distributed to those who request it, so that it can begin to help those who want to assess workload, and so that user feedback can guide future system revisions.

Although decision support systems are not intended to replace the humans after which they are modeled, it is hoped that systems such as WC FIELDE will encourage increased workload evaluation in the early stages of man-machine system design, to ensure greater economy, safety, and productivity. Also, as more knowledge about workload is incorporated into the system we should come closer to a true understanding of the nature of workload and the many factors affecting how it is expressed in the human operator.

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A SIGNAL DETECTION ANALYSIS
OF BIMODAL ATTENTION:
SUPPORT FOR RESPONSE INTERFERENCE

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by

Patricia Ann Casper

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of

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To my mother and father, Jean Ann and James Earl Lakin, whose unconditional love and support provided the perfect environment for me to strive for all that I hoped and dreamed I could achieve. I couldn't have asked for more. Thank you both.

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ABSTRACT

Casper, Patricia Ann. M.S., Purdue University, May, 1986.
A Signal Detection Analysis of Bimodal Attention: Support
for Response Interference. Major Professor: Barry H.
Kantowitz.

In an experiment designed to distinguish perceptual from response sources of dual-task interference subjects performed a concurrent auditory and visual two-choice (same - different) reaction time task where signals were possible in either, both, or neither channels on a trial (an inclusive-OR task). Two variables were manipulated in order to obtain more error data; the interstimulus interval (ISI), (1200 msec or 1600 msec), and the speed instructions. The subjects were either given no reaction-time (RT) deadline or were given a deadline equal to 80 % of the RT mean from an earlier block with the same ISI. Also included were single-stimulation control conditions for both of the modalities at both of the ISIs. Performance measures examined were RT, d' , and beta.

The results of the experiment showed better performance in the single-stimulation control conditions than in any of the double-stimulation conditions. Cross channel analysis of the data found that d' in the auditory channel was worse

on on trials with a concurrent visual change, visual response, or greater than median visual RT, while visual d' was independent of the type of auditory trial. The overall superiority of performance in the visual channel supported a visual dominance explanation of auditory - visual timesharing, whereby visual inputs are given processing priority and any leftover capacity is used for processing auditory information.

Further contingent analyses revealed that executing a response in the opposite channel was the major cause of dual-task interference, a finding not supported by perceptual interference theories.

INTRODUCTION

Scientists have long been engaged in the difficult task of characterizing the nature of human attention. Past and present efforts at elucidating this hypothetical entity that allows us to select which information to process in a world full of competing stimuli have yielded diverse results. Early work in the area portrayed attention as a "filter" that could only accept information from one source at a time, serving to protect a limited capacity channel from information overload (Broadbent, 1958). Subsequent experimentation found that some of the information previously thought to have escaped awareness (that which had not passed the filter) had indeed made contact with memory, providing evidence of a wider beam for the "spotlight" of attention (Moray, 1959; Triesman, 1960).

Recent work in the area of divided attention, or timesharing, has turned up data that is increasingly supportive of a dynamic system of attention, where multiple patterns of interactions can be obtained by manipulating task demands and the attention allocation policies of subjects (Wickens, 1980, 1984; Navon & Gopher, 1980). A different picture of attention appears to emerge with each

new methodology designed to study it. Broadbent (1982) provides a more detailed history of the last three decades of progress in the field of attention than may be addressed here.

The present investigation will address the issue of the locus of attention in bimodal timesharing tasks, that is, which stages of processing show the most interference when tasks in different modalities are combined. The two stages of concern are the early, or perceptual stage and the later, response stage. A brief review of the current timesharing literature will be presented, leading up to the description of an experiment designed to distinguish perceptual from response interference. After the results of the experiment are presented an attempt will be made to fit the findings into the current picture of attention in cognitive psychology.

Theoretical approaches to the study of attention

Much of the work that has been done in the area of attention in the past decade or so can be classified into two main approaches: the structural approach and resource theory. The structural approach is focused on the architecture of the information processing system, and in particular, on finding the bottlenecks or places in the system where limits in processing are observed to occur. Within the structural approach there are several theories

that differ on where the main sources of interference are found. One group of researchers proposes that the major sources of dual-task interference lie in the early stages of processing, when more than one stimulus must be encoded for processing. Many experiments using a secondary probe reaction-time task to measure the amount of capacity demanded by a primary task (see Kantowitz, 1974; McLeod, 1978) have found evidence that the encoding stage of processing does indeed consume capacity (Millar, 1975; Schwartz, 1976; & Proctor & Proctor, 1979). This was contrary to previous findings of no perceptual interference when multiple stimuli are encoded (Posner & Boies, 1971).

Further evidence of an early locus of attention has been reported by Triesman & Davies. Assuming that redundant information should improve memory Triesman & Davies (1973) presented the same stimuli to either the same input modality or to different modalities. Recall was worst when information was presented simultaneously to one modality and best when information was presented to different modalities. Triesman and Davies accepted these findings as evidence of separate modality-specific perceptual processing mechanisms that are unable to effectively process multiple inputs.

One final group of experiments supporting perceptual interference in attention is found in the signal detection literature. Early signal detection experiments by Moray & O'Brien (1967) and Moray (1970a) supported selective

attention work by Triesman & Geffin (1967) through findings of reduced detectability for rejected messages. In addition, positive correlations between detectability and bias (beta) scores suggested that attention is shared in divided attention tasks with the greatest decrements resulting when simultaneous targets occur.

The second group of researchers within the structural group assumes perceptual interference to be minimal at most, with the majority of interference occurring later in the system, during response-processing stages. The approach used in the present experiment falls into this category. The methodologies used by this group have ranged from what could be classified as psychophysical, or signal detection experiments (Ostry, Moray, & Marks, 1976; Moray, Fitter, Ostry, Favreau, & Nagy, 1976; Sorkin, Pohlmann, & Woods, 1976), to experiments using semantic stimuli (Duncan, 1980), to experiments using response force as a dependent variable (Kantowitz, 1973). A number of experiments from this class shall be covered in some detail in the next section.

The third class of theories under the structural approach consists of those that cast attention in a more dynamic role than the first two. Theories in this class assume that interference can occur at a number of locations in the system. This approach predicts that multiple inputs can be processed simultaneously but that the cost (in terms of effort or capacity) increases with the depth of

processing (Johnston & Heinz, 1978; Triesman & Davies, 1973). Thus it is "cheaper" in terms of capacity expenditure to process simultaneous inputs on the basis of physical information about the inputs than to process simultaneous inputs for semantic information, although in the second case the two tasks can still be performed simultaneously. The cost of late selection would be paid in the form of confusion errors or delayed responses (misses if the task is fast-paced) to one or both of the inputs, however. This idea was formulated as early as 1956, when Broadbent found that two tasks could be timeshared with a cost in the delay but not in the accuracy of responding (Broadbent, 1956b).

The second major group of theorists consists of those who subscribe to resource theory, an approach similar in some respects to the dynamic structural approach just mentioned. Resource theory assumes the existence of an intervening variable, a resource, that is consumed when a task is performed. Resource theory has followed somewhat the same evolutionary history as the structural theories of attention. In the early years of the structural approach, single bottlenecks were first proposed, then as more and more empirical exceptions to the single bottleneck were found the architecture of the information channel was changed to portray a more complex system having multiple bottlenecks (the dynamic structural approach). Resource

theory has gone the same route. In its original formulation resource theory assumed that a single pool of undifferentiated capacity fueled the entire processing system, with task difficulty and task priority determining the allocation of resources to each task (Kahneman, 1973; Norman & Bobrow, 1975; Navon & Gopher, 1979). Detriments in performance occurred when both tasks demanded more than the total available supply of resources. When single resource theory could not account for a number of findings of perfect timesharing (Allport, Antonis, & Reynolds, 1972) and of difficulty insensitivity (Wickens, 1976) it was revised to include the concept of many pools of resources. Multiple resource theory proposes that there are several separate "pools" of resources (capacity) available for different types of processing, and that tasks drawing on separate sources of capacity will interfere with each other less than tasks using the same sources. Separate pools have been suggested for modalities of processing (visual & auditory), codes of processing (spatial & verbal), stages of processing (encoding, central processing, & responding), and responses (manual & vocal) (Wickens, 1980, 1984). Although some have questioned the utility of inventing new sources of capacity for each new empirical finding (Kantowitz, 1985) its supporters have met with some success in predicting the patterns of interference for certain pre-specified task combinations. Multiple resource theory would have few

problems accounting for the previously mentioned findings of Triesman & Davies (1973), for example, since it posits separate sources of capacity for auditory and visual perceptual processes.

Now that the general theoretical climate, albeit varied, has been presented, several studies bearing directly on both the conceptual framework and the methodology of the current experiment will be discussed.

A signal-detection analysis of bimodal timesharing

The present investigation uses the methods prescribed by signal detection theory (Tanner & Swets, 1954) to support the position that attentional effects are mostly due to a limited supply of (or greater demand for) response resources. A signal-detection analysis of performance in bimodal timesharing tasks is potentially a powerful method for localizing processing bottlenecks. This approach provides invaluable tools for separating an individual's bias (induced by motivation) in a task from his actual sensitivity to the experimental stimuli. The method is also experimentally economical in that it allows interpretation of previously wasted error data.

Most signal detection analyses of multi-channel timesharing use one of two paradigms : the exclusive-OR (XOR) paradigm or the inclusive-OR (IOR) paradigm. In the XOR task signals requiring a response may occur in one, the other, or neither channel on any given trial, but never in

both channels simultaneously. In the IOR task, however, signals can occur in one, the other, neither, or both channels on a given trial (Moray & O'Brien, 1967). Thus both tasks require simultaneous monitoring of two channels, but only the IOR task requires that the subject make concurrent responses.

Using an IOR task, Sorkin, Pohlmann, & Gilliom (1973) found cross-channel interference associated with a signal event in the opposite channel. Sorkin & Pohlmann (1973) used the XOR task to create a situation where the subject had to monitor two channels simultaneously but never had to make simultaneous responses. In this task, as compared to the IOR task, detection levels on the two channel task approached those of the single channel control condition, and no evidence of cross-channel interference was found, supporting a post-perceptual locus of dual-task interference.

In a binaural signal detection experiment Sorkin, Pohlmann, and Woods (1976) instructed subjects to simultaneously detect the presence of briefly-presented signals at two different frequencies. The task was an IOR task. Results confirmed that performance on one channel was affected by the nature of event occurring in the other channel -- specifically that a signal or a "yes" response in one channel interfered with signal detection performance in the other channel. For each trial the total energy (signal

and noise combined) for each channel was computed. No effect of the energy level in the other channel on d' or beta was observed. Further, the energy level in a channel was not significantly correlated with the type of response (yes versus no, correct versus incorrect) occurring in the other channel. Sorkin et al. concluded that since an energy-related explanation of cross-channel interference had failed, the source of the observed dual-task decrement must be located further into the information-processing system.

Under the assumption that each sensory system is characterized by its own characteristic pattern of internal noise, Eijkman and Vendrik (1965) sought correlations between the noise from different channels in order to support their hypothesis that auditory and visual signal detection proceeds independently. In the experiment, subjects concurrently detected increments in the intensity of auditory and visual stimuli. The total duration of the signals was 2 seconds, with an increment (of unspecified magnitude) possible after 1 second of presentation.

Eijkman and Vendrik found that the probability of a false alarm (responding to a non-increment) in one channel was not influenced by the presence or absence of a stimulus in the other channel, and further that the probability of a hit (responding correctly to an increment) was not related to the type of event in the other channel. Calculations of the detectability, or d' , in a channel revealed that

detection in one channel under dual-task conditions was identical, if not better than that occurring with a single-task. Comparable results from similar experiments have been reported by Pastore & Sorkin (1972). Further, Eijkman and Vendrik found that the noises present in the two channels were not correlated. Contrary to these results of independence a nearly perfect correlation was found between the noise characteristic to each of the channels when the task was to detect increments in stimulus duration.

Eijkman and Vendrik interpreted their results as evidence that there are two separate modality-specific centers for intensity detection but only one "duration center". Eijkman and Vendrik's results cannot be accepted as conclusive evidence of independent auditory and visual information processing because of several factors. First, the task could be considered "perceptually easy" since the stimuli were constantly "on" and the subject did not have to rely on memory to hold a representation of the previous intensity level. Second, the intensity increments given to the subjects were unreported. If they were of large enough magnitude they could have accounted for their results of no dual-task interference. Finally, the task was paced relatively slowly, and could have been a fairly easy task to perform (2 second stimulus presentations with an 8 second ISI). Some researchers have proposed that divided attention effects only occur in difficult task situations (Triesman &

Davies, 1973; Shiffrin & Grantham, 1974) where difficulty is manipulated by the type of task used (verbal versus signal detection) or by the rate of presentation of material. A tri-channel (auditory, visual, and tactile) signal detection experiment conducted by Shiffrin & Grantham (1974) found results similar to Eijkman and Vendrik (1965) when a single-trial paradigm was used, and results of cross-channel interference replicating Sorkin, Pohlmann, & Gilliom (1973), when a repeated-trials procedure was used. Task difficulty appears to play an important role in the degree to which multiple tasks can be effectively timeshared, a premise long held by resource theory.

The present experiment was in part a replication of a previous related experiment (Casper & Kantowitz, 1985) in which the temporal structure and pattern of change within sequences of auditory and visual stimuli were manipulated in order to examine the nature of cross-channel dependencies in the dual-task situation. In the related experiment, subjects were instructed to press a response key (one for each modality) upon detection of changes in auditory and visual stimuli. The sequences of 100 bimodal stimulus presentations consisted of red or blue rectangles and high- or low-frequency tones. A change was defined as the occurrence of a stimulus that was different (in pitch or in color) from the previous stimulus. The task was an IOR task (defined previously) whereby changes could occur in the

auditory channel, the visual channel, both channels simultaneously, or neither channel. Sequences had either a 2:1 or a 1:1 ratio of visual to auditory stimuli and either a fixed (with changes on every other trial) or a random pattern of changes, where the overall probability of a change in the sequence was .5. There were no sequential dependencies within or between the channels, as is sometimes the case in other signal detection experiments where no target will be presented for a specified period following a prior target. In the 2:1 condition a visual stimulus was presented once every 1600 milliseconds, with a corresponding auditory stimulus occurring only once every 3200 milliseconds. In the 1:1 condition both a visual and an auditory stimulus occurred every 1600 milliseconds. Dependent measures included the percentage of hits and false alarms (later transformed into d' scores), reaction time measured in milliseconds, and d'^2/RT , a measure reflecting information processing rate (Taylor, Lindsay & Forbes, 1967).

This paradigm differs from the traditional signal detection experiment in a subtle but nonetheless important way. On any trial of the typical signal detection task, a signal is defined as the presence of a sensory stimulus (energy) either alone or embedded in noise. In the Casper & Kantowitz experiment a sensory stimulus was presented on every trial (except in the 2:1 case) and a signal was

defined as the occurrence of a sensory stimulus having a different value than the previous one. Thus the task could be considered a same-different recognition task where the subjects only respond to "different" stimuli, a "c-reaction" (Donders, 1969). This paradigm presumably involves processing at a deeper cognitive level than the strict detection paradigm and could be considered roughly equivalent to the task used by Eijkman & Vendrik (1965) in which subjects detected increments in intensity of stimuli.

The results of the Casper & Kantowitz experiment verified that performance in both channels (modalities) was better in the 2:1 than the 1:1 condition, and that a fixed pattern of change was easier to detect than a random pattern of change. In addition, in the 2:1 randomly-changing sequences, a tone in the auditory channel interfered with detection of changes in the visual channel. That is, performance in the visual channel was better on those trials on which no tone was presented than on trials where an auditory and a visual stimulus were presented concurrently. Further, in the 1:1 randomly-changing condition, a target (a change in the color of the rectangles) in the visual channel caused a decrease in auditory sensitivity (d'), but the trial type (target, no target) in the auditory channel had no effect on visual channel performance. These results were reflected in both d' and d'^2/RT transformations, and were supportive of a response interference explanation of the

dual-task decrement. The presence of an event requiring a response in one channel had a deleterious effect on performance in the other channel. Ideally, the effect of actually making a response in one channel on performance in the other channel should have been analyzed, but the lack of sufficient error data precluded such an analysis.

Casper and Kantowitz interpreted the results from the 1:1 condition as evidence in support of either the visual dominance phenomenon (Posner, Nissen, & Klein, 1976) or as evidence of a bias in favor of the visual over the auditory channel. A visual dominance interpretation of the results credits the intrinsically greater alerting capabilities of the auditory signals with causing more resources to be allotted to the visual channel; it is "protected" from auditory interference. Alternatively, an implicit bias for attending to the visual stimuli may have been created since there was a greater number of visual than auditory stimuli overall in the experiment. The subject may have been led to believe that the visual stimuli were of greater importance due to their greater number, despite instructions to pay equal attention to both channels. The present experiment includes the same number of auditory and visual stimuli (only the 1:1 randomly-changing sequences from the first experiment were used) to more effectively test the visual dominance explanation of auditory-visual timesharing. If visual dominance, and not a implicit bias towards responding

to visual stimuli was responsible for the results of the previous experiment, the same pattern of results should show up in the present experiment where no implicit biases exist.

The present experiment

At test in the present experiment were the classes of theories known as perceptual interference theories and those known as response interference theories. Both types of theories agree that capacity is limited somewhere in the system. They disagree on where the greatest amount of interference will occur in the system given multiple stimuli. The proposed experiment was designed to specifically test models that allow essentially parallel perceptual processing but predict greater impairments later in processing when simultaneous inputs compete for capacity (Kantowitz & Knight, 1976; Sorkin, Pohlmann, & Woods, 1976; & Shiffrin & Grantham, 1974). This would include resource theories where each modality has it's own pool of perceptual resources while response processes share a common pool of resources, and structural theories with limited capacity available to later stages of processing.

The experiment employed a simultaneous auditory and visual signal detection paradigm, where subjects responded to random changes in pitch of the auditory stimuli and changes in the hue of the visual stimuli. As in the previous experiment, an IOR task was used. Subjects were told to divide attention equally between the two modalities,

or channels, as they will be called. Within an experimental condition subjects were presented simultaneous auditory and visual stimuli occurring at a constant inter-stimulus interval throughout the sequence, with the subjects understanding that for a response to be counted as correct they had to respond before the presentation of the next pair of stimuli. Subjects performed under conditions of short and long inter-stimulus intervals, normal and speed-emphasized instructions, and single- and double-stimulation (Kantowitz, 1974). The independent variables were chosen for their ability to increase error data overall (misses and false alarms) in order to provide a richer data base for subsequent analysis.

Predictions

Overall performance (as measured by d') should be worse in both the shorter ISI and speed instructions conditions. Since attention is shared between the two tasks, less time allotted between trials (a shorter ISI) should result in poorer detection.

The accuracy and the latency of responses in a channel should depend on the latency of a correct response in the other channel. In particular, d' on one task should be inversely related to the latency of a response in the other task, and the reaction time for one task should be positively correlated with the latency of a response for the other task. This prediction assumes that the processing

system has an overall limit on capacity (induced either by overall limits or by limits at a specific stage of processing), and that large depletions of that capacity by one of the tasks should produce impairments in performance of the other task. In other words, overall capacity is shared between the two tasks. Suppose processing on one task, task A, takes 90% of the ISI to complete. Unless processing on the other task, task B, can either proceed in parallel with task A or can be completed after task A in the remaining 10% of the ISI, performance on task B should suffer. Once a response to a task is made, capacity that was previously used for that task can be freed for the remaining task, providing, of course that the two tasks are drawing on the same capacity stores. A finding of no correlation between accuracy and latency in the two channels would suggest that either the two tasks are drawing on separate pools of capacity or that the tasks are not difficult enough to use up the supply of capacity.

Given a generalized limit on system capacity, it is further predicted that performance within a channel should be poorer on those trials when a signal (in this case, a change) occurs in the other channel than on non-signal trials (where the stimulus does not change). It is hypothesized that the high correlation between signals and their associated responses is the reason for poorer performance on opposite channel signal trials, since

response processes are assumed to require more capacity to execute. It follows then, that performance in a channel should be worse on trials where any kind of overt response (either a hit or a false alarm) occurs in the other channel than on trials where no overt response occurs in the other channel. A signal can occur in the opposite channel and not disrupt detection performance in the current channel, as long as no response is executed in the other channel.

Table 1 gives a summary of the d' contingency predictions for both perceptual and response-oriented theories for the present experiment. The logic behind the predictions in the table arises from the fact that responses are executed for hit and false alarm trials but not for correct rejection or miss trials. Note that a perceptually-based theory would predict that detection in one channel would be degraded by the presence of a signal (occurring on hit and miss trials) in the opposite channel, since perceptual processes are supposed to be most affected by divided attention. A response conflict theory predicts that a response in the other channel (either correct or incorrect) momentarily diverts processing capacity away from the present channel. This interpretation would predict no difference between performance in a channel given either type of response event in the other channel, however. Those trials should have a combined lower d' than that on trials where there is a correct rejection or a miss in the other

channel, since response processes presumably consume more capacity.

While this experiment will be able to isolate early stage from late stage interference it will not distinguish results supported by a structural theory from those supported by resource theory. Both theories are capable of attributing capacity shortages to different locations in the system. The study should, however, prove successful in demonstrating which parts of the system share a limited source of capacity and which parts may draw on separate resources.

METHOD

Subjects

Sixteen male undergraduate students from an introductory psychology course participated in the experiment. Only subjects with normal hearing and color vision were allowed to participate. Each subject received one hour of credit for his participation, partially fulfilling a class requirement for research involvement.

Apparatus

The auditory stimuli used in the experiment consisted of high- and low-frequency tones of 3615 Hertz and 1420 Hertz at 75 dB (A) SPL that were presented to the subjects over Grason Stadler (model TDH39-300Z) headphones. A Gen Rad GR 1565-D Sound Level Meter was used to measure the intensity of the auditory stimuli. A Realistic model SA-10 solid state stereo amplifier was used to amplify the tones. The visual stimuli consisted of 1.25 cm by 2.5 cm vertical red and blue rectangles presented on a Sony Trinitron 12-inch color television subtending 2.41 vertical degrees of visual angle. The television was situated 60 cm in front of the subjects. Due to the imprecise nature of the display

equipment the intensities of the visual stimuli were unable to be controlled but were measured at 5.5 footlamberts for the red rectangles and 23.5 footlamberts for the blue rectangles. The device used to calibrate the visual stimuli was a Tektronix J16 digital photometer using a J6523 1° Narrow angle luminance probe at a viewing distance of 60 cm. An Apple II computer was used to generate the tones and produce the rectangles on the television screen. Both the tones and the rectangles were presented for a duration of 100 milliseconds.

Subjects responded by pressing one of two response keys located on the table directly in front of them. For half of the subjects the tone key was on the left and the rectangle key was on the right, and for the other half of the subjects the key placement was reversed. The static force required to depress the keys was 60 grams. Responses were sent to the computer through the binary input ports of a Cyborg model 91A ISAAC computer interface clock which measured response times to the nearest millisecond.

Procedure

The stimuli were either simultaneously- (in double-stimulation) or singly-presented (single-stimulation) sequences of discrete presentations of auditory and visual signals. Figure 1 shows the relationship between the auditory and the visual sequences in the double-stimulation conditions. Within an auditory or visual channel, the

probability that a signal differed from the previous one was .5. A table of random numbers was used to predetermine the random presentations of the two levels of stimuli in each modality. In the double-stimulation blocks, the sequences had a 1:1 ratio of visual to auditory signals, where every auditory signal was presented simultaneously with a visual signal.

The independent variables manipulated in the experiment were the interstimulus interval (ISI) as measured from stimulus onset to stimulus onset, and the speed instructions given to subjects. There were two levels of ISI, 1200 and 1600 msec, and two levels of speed instructions, regular and fast. A within-subjects design was used, with all of the subjects receiving both double- and single-stimulation conditions and two levels each of ISI and speed instructions. Table 1 gives the order of the experimental conditions given to each subject. The four single-stimulation blocks were counterbalanced across subjects using a balanced Latin square design. During the speeded blocks the subject was instructed to respond within a time limit that was equal to 80% of his reaction time (the mean of auditory and visual RT) from the earlier block with the same ISI. The subject repeated a speeded block until he achieved a mean RT of less than or equal to the designated goal.

A sequence consisted of 50 stimulus presentations resulting in a total sequence duration of 1 minute and 20 seconds for the 1600 msec ISI condition and exactly 1 minute for the 1200 msec condition.

When the subjects arrived at the laboratory, the experimenter read a brief introduction. Subjects were told that they would first receive training on tasks requiring their attention to two things at once, and that they would later be tested on the tasks that they would learn.

Single-stimulation training. Training was first given on the single-stimulation task. Subjects were instructed to attend to a sequence of tones or rectangles and to respond by pressing the appropriately-labelled key when they noticed that a change occurred in the stimuli during a sequence. A change was defined as any stimulus presentation that was different from the previous stimulus in a particular sequence; for example, if a red rectangle is presented, followed by a blue rectangle on the next presentation, the subject should press the key labelled "rectangles". If another red rectangle is presented after the blue rectangle, another "rectangle" response is required. The subjects were informed that a change may or may not occur each time that a stimulus is presented. Subjects were told to use only one hand to respond, and to place their other hand in a comfortable position somewhere away from the unused response key. Two sequences were presented during single-

stimulation training--a randomly-changing sequence of tones, and a randomly-changing sequence of rectangles, both with a 1600 msec ISI. Both sequences used in training consisted of 50 stimulus presentations. Subjects were instructed to leave their headphones on during both single-stimulation sequences.

Double-stimulation training. Next the subjects were trained on two double-stimulation tasks. Subjects were told that the stimuli in either modality may or may not change on any given presentation, and that a change may occur in none, one, or both sequences on any given presentation. For example, the color of the rectangle may change from blue to red, and, in addition, the tone may change from high to low, thus calling for responses on both keys. Another possible response situation is one where the pitch of the tone changes, but the rectangle is the same color as that on the previous presentation. In this case, only a response on the tone key is required. The subjects were instructed that recognizing changes in the tone sequence is equally as important as recognizing changes in the sequence of rectangles. In both training blocks the subjects were informed that only responses occurring before the onset of the next stimulus after a change had occurred would be counted as correct. The response interval following a stimulus change was 1600 msec. Subjects were also told that following a sequence of stimulus presentations their mean

reaction times to the tones and the rectangles would be displayed (in milliseconds) on the screen in front of them.

Testing. Upon completion of training in the reaction time tasks, the testing session began. Subjects were presented with a double-stimulation sequence for which the task was the same as in the training session--subjects were to attend to both the tone sequence and the rectangle sequence and press the appropriate response key when they detected a change in any stimulus. Subjects were then presented two single-stimulation sequences, followed by another double-stimulation sequence, all of which had a 1600 msec ISI. This procedure was then repeated except with a 1200 msec ISI. The last half of the experiment consisted of four double-stimulation blocks, two at each ISI, all imposing a response criterion of 80% of the earlier double-stimulation block's mean RT for the same ISI.

RESULTS AND DISCUSSION

Overall performance

Overall errors. Errors were separated into false alarms (commission errors) and misses (omission errors), and analyzed separately for the auditory and visual data. Table A1 (see Appendix) gives the auditory and visual overall error data. There was no effect of ISI or of speed instructions on the percentage of false alarm errors in either modality.

For both the auditory and the visual channels the 1200 msec ISI condition had a higher number of misses than the 1600 msec condition, $F(1,15) = 10.56, p = .005$ (auditory), $F(1,15) = 8.63, p < .01$ (visual).

Overall d'. d' scores were calculated separately from the hit and false alarm data for each subject in each condition. d' scores for the tones in the 1200 and 1600 msec ISI conditions were 2.51 and 2.81, $F(1,15) = 9.3, p < .01$. The visual means were 2.69 and 3.02 in the short and long ISI conditions, $F(1,15) = 9.3, p < .01$. No effect of speed instructions, $F(1,15) = .03, p > .05$ was observed on d' scores. Unless otherwise noted, all data presented were

averaged over the first and second blocks of a particular condition.

Overall reaction time. Figure 2 presents mean reaction time as a function of ISI and speed instructions for the auditory and visual data. Unless specifically stated otherwise, all reaction time analyses were based on correct responses only. Reaction times in the short ISI condition were significantly faster than those in the long ISI condition, $F(1,15) = 54.55$, $p < .001$, and reaction times in the fast speed instructions condition were shorter than in the regular speed instructions condition, $F(1,15) = 243.85$, $p < .001$. Overall, reaction times to the visual stimuli were faster than those to the auditory stimuli, $F(1,15) = 2.56$, $p < .001$. There was also an interaction between ISI and type of stimulus, $F(1,15) = 8.49$, $p = .01$, and between speed instructions and block, $F(1,15) = 4.26$, $p = .05$.

Single-Stimulation Results. Separate analyses were done on the auditory and visual d' , beta, and reaction times from the single-stimulation blocks. None of the six single-stimulation analyses approached significance. Single-stimulation performance was also compared to double-stimulation performance, with auditory and visual d' scores as a function of the level of stimulation given in Figures 3 and 4.

The lowest d' scores were in the fast speed instructions conditions with higher scores in the regular speed instructions and single-stimulation conditions, respectively, for both the auditory, $F(2,30) = 31.35$, $p < .001$ and the visual channels, $F(2,30) = 9.48$, $p < .001$. t-tests performed on the auditory d' means revealed that the difference between regular- and fast paced double-stimulation was not significant, $t(30) = .66$, $p > .05$. d' in the 1600 msec ISI condition was higher overall than that in the 1200 msec ISI condition for the visual channel, $F(1,15) = 9.67$, $p < .01$. There was also a significant difference between the 1600 and the 1200 msec ISI d' scores in the single-stimulation condition for the visual channel, $t(30) = 2.42$, $p < .05$.

The beta scores were also analyzed as just described. Table A2 (see Appendix) gives auditory and visual beta scores as a function of the level of stimulation.

Figures 5 and 6 give auditory and visual reaction times for the 3 levels of stimulation and the 2 levels of ISI. Auditory reaction time (Figure 5) was fastest in the single-stimulation condition, followed by the fast speed instructions and then the regular speed instructions conditions, respectively, $F(2,30) = 120.13$, $p < .001$. reaction times in the 1200 msec ISI were significantly faster than those in the 1600 msec ISI condition, $F(1,15) = 24.07$, $p < .001$, with t-tests revealing the source of the

main effect in the ISI differences in the two double-stimulation conditions. 1200 msec reaction times were faster than 1600 msec reaction times in the regular-, $t(30) = 6.05$, $p < .001$, and fast-paced, $t(30) = 3.82$, $p < .001$ double-stimulation conditions, but not in the single-stimulation condition, $t(30) = 1.17$, $p > .05$. There was a significant interaction between level of stimulation and ISI, $F(2,30) = 5.79$, $p < .01$. The differences between 1600 msec regular- and fast-paced double-stimulation, $t(30) = 8.93$, $p < .001$ and between the 1200 msec double-stimulation conditions, $t(30) = 6.69$, $p < .001$, were significant.

The level of stimulation affected visual reaction times in a pattern similar to the auditory reaction times (see Figure 6), $F(2,30) = 53.58$, $p < .001$, as did ISI, $F(1,15) = 15.33$, $p = .001$. In addition, these two factors interacted significantly for the visual data $F(2,30) = 7.22$, $p < .005$. The regular speed instruction condition produced significantly longer reaction times than the fast speed instruction condition when the ISI was 1200 msec $t(30) = 7.93$, $p < .001$. The two levels of ISI were not different, $t(30) = .44$, $p > .05$, from each other in the single-stimulation condition, but reaction times in the 1200 msec ISI condition were faster than in the 1600 msec ISI conditon in both the regular and fast speed instructions conditions, $t(30) = 4.63$, $p < .001$, $t(30) = 3.53$, $p < .01$, respectively.

Cross-channel results

The most important results from the experiment are those that illuminate how performance is traded off between the two tasks as the demands of each task change from trial to trial. Analyses such as these are crucial in that they reveal momentary fluctuations in performance associated with specific limitations in the system. Contrary to conventional data analysis techniques that collapse data across trials and compare different conditions, contingent analyses allow us to examine the micro structure of attention by comparing trials of one type to trials of a different type. The double-stimulation data were analyzed for a number of contingent probabilities, the first of which is performance in a channel dependent on the latency of the response in the other channel.

Latency of response. d' , beta, and RT scores for the auditory and visual double-stimulation data were analyzed by the magnitude of the reaction time occurring in the other channel (given that a correct response was made in the other channel). Performance on trials having greater than the block median reaction time in the other channel was compared to performance when the RT in the other channel was less than the block median. Figure 7 gives auditory d' as a function of RT type in the visual channel. Consistent with preliminary assumptions of a generalized limit on capacity, d' was higher on trials where there was a fast

visual response, $F(1,15) = 5.22$, $p < .05$. There were no significant effects of ISI, $F(1,15) = 1.9$, $p > .05$, or speed instructions, $F(1,15) = .93$, $p > .05$ on auditory d' scores.

Figure 8 shows visual d' by auditory trial type ($>$ median RT, $<$ median RT) for the 2 levels of ISI. The latency of the auditory response had no effect on the visual d' scores, $F(1,15) = .24$, $p > .05$. d' was, however, higher in the 1600 msec ISI condition, $F(1,15) = 7.11$, $p < .05$, and there was an interaction between ISI, RT type and block, $F(1,15) = 5.45$, $p < .05$. Auditory and visual beta scores can be found in the Appendix (Table A3).

The auditory and visual reaction times were also analyzed dependent on the size of the opposite channel reaction time. When averaged over blocks 1 and 2 of all of the double-stimulation conditions, reaction time given a greater-than-median response in the other channel was greater (indicating poorer performance) than reaction time given a less-than-median response in the opposite channel. For the auditory channel, reaction time given a long visual response was 450 while reaction time given a short visual response was 308, $F(1,15) = 34.23$, $p < .001$. For the visual channel, reaction time given a long auditory response was 441 and with a short auditory response it was 270, $F(1,15) = 71.59$, $p < .001$. In addition, block 2 reaction times were faster than block 1 (342 vs 368, $F[1,15] = 8.25$, $p = .01$). These data complement the results of the d' analyses

described in the previous paragraph where performance was impaired given a long response in the other channel. The auditory and visual tasks appear to be reliant on the same source of capacity, although this analysis alone does not indicate whether all or just some sources of capacity are shared by both tasks. Excessive capacity demands by one process in the system could possibly produce results of this type.

Change versus no change. The d' data were also analyzed dependent on a concurrent change versus no concurrent change in the opposite channel. Note that a "change" trial is a trial where there was a) a perceptual signal, b) an internal translation signal linked to a response, and c) possibly a response. Figure 9 shows mean d' in the auditory channel as a function of the trial type in the visual channel. Consistent with earlier predictions, d' was higher in the 1600 msec ISI condition than in the 1200 msec ISI condition, $F(1,15) = 7.81$, $p = .01$, and higher on trials where there was no change in the visual channel, $F(1,15) = 34.31$, $p < .001$.

Figure 10 gives the results from the same analysis on the visual data. Analysis of variance revealed the same ISI trend for the visual data as was found in the auditory data, $F(1,15) = 4.74$, $p < .05$, but surprisingly, no difference in d' scores between the two auditory trial types, $F(1,15) = .56$, $p > .05$.

Auditory and visual reaction times as a function of trial type in the opposite channel may be found in the Appendix (Table A4).

Response versus no response. The next analysis compared auditory and visual d' on trials where the subject made a response in the other channel to d' on trials where the subject made no response to the other channel. Figure 11 presents auditory d' as a function of trial type (response, no response) in the visual channel. It can be seen that d' on trials with no visual response was higher than d' on trials where a visual response was made, $F(1,15) = 6.66$, $p < .05$. In other words, any kind of response (correct or incorrect) to the visual channel was disruptive of processing in the auditory channel. d' was also higher in the 1600 msec ISI condition than in the 1200 msec condition, $F(1,15) = 5.07$, $p < .05$. A significant interaction between speed instructions and block was found, $F(1,15) = 4.79$, $p < .05$.

Figure 12 gives visual d' as a function of the trial type (response, no response) in the auditory channel. Performance in the visual channel did not vary with auditory trial type, $F(1,15) = .09$, $p > .05$. As was reported in Casper & Kantowitz (1985), processing of visual information appears to have been protected to the extent that performance on the auditory task suffered. Visual d' was also higher in the 1600 msec ISI condition, regardless of

the type of speed instructions given, $F(1,15) = 6.11$, $p < .05$. There was a 3-way interaction between ISI, auditory trial type, and block, $F(1,15) = 4.36$, $p = .05$. Auditory and visual beta as a function of trial type (response, no response) may be found in the Appendix, in Table A5.

Table 3 presents the RT means for both the auditory and the visual channels as a function of ISI, speed instructions, block, and trial type (response, no response) in the other channel. To help the reader, the means averaged across conditions are presented in the text. For the auditory channel the short and long ISI mean RTs were 333 and 426 msec, $F(1,15) = 65.14$, $p < .001$, respectively. The regular speed emphasis condition mean was 451 while the fast speed emphasis condition mean was 309, $F(1,15) = 343.8$, $p < .001$. Block 1 mean reaction time was 389 and block 2 RT was 371, $F(1,15) = 5.21$, $p < .05$. No effect of visual trial type, $F(1,15) = .004$, $p > .05$, was observed for the auditory reaction time data. Two-way interactions were found between ISI and speed instructions, $F(1,15) = 6.74$, $p < .05$, speed instructions and visual trial type, $F(1,15) = 9.31$, $p < .01$, and between speed instructions and block, $F(1,15) = 5.9$, $p < .05$. There was also a significant three-way interaction between ISI, speed instructions, visual trial type, and block, $F(1,15) = 6.39$, $p < .05$.

Visual mean RTs in the short and long ISI conditions were 326 and 388 msec, $F(1,15) = 43.15$, $p < .001$,

respectively, while RTs in the regular and fast speed instructions conditions were 416 and 297 msec, $F(1,15) = 127.59$, $p < .001$. The block 1 mean RT was 367 and block 2 mean reaction time was 347, $F(1,15) = 4.32$, $p = .05$. No effect of auditory trial type was found for the visual reaction time data, $F(1,15) = .02$, $p > .05$. Making a response to one of the channels (regardless of correctness) did not affect how long it took subjects to respond to the other channel.

Hit, false alarm, correct rejection, miss. Next, the auditory and visual d' , beta, and RT scores were analyzed according to the type of response occurring in the opposite channel -- hits versus false alarms, and correct rejections versus misses. The reader is encouraged to refer back to Table 1 in the introduction which lists the specific predictions regarding these contingent analyses for the two opposing classes of theories. Figure 13 shows auditory d' as a function of trial type in the visual channel. The data for these analyses were taken from the second block of testing in each experimental condition. In the 1600 msec ISI speeded-instructions condition two subjects out of sixteen did not make any errors in one of the channels, so the means for those two subjects in the d' given a miss and the d' given a false alarm cells (the error cells) were set equal to the mean of those subjects' d' given a correct

rejection and d' given a hit cells (the correct response cells).

As is commonly found in two-channel signal detection studies (Eijkman & Vendrik, 1965; Moray et al., 1976; Ostry et al., 1976; Sorkin & Pohlmann, 1973), there was no difference between auditory d' given a visual hit and auditory d' given a visual false alarm, $F(1,15) = .60$, $p > .05$. Contrary to earlier predictions, auditory d' given a visual correct rejection was greater than auditory d' given a visual miss, $F(1,15) = 8.87$, $p < .01$, instead of being the same. The interaction between ISI and type of response (CR or M) $F(1,15) = 4.6$, $p < .05$, was significant. A t-test, $t(45) = 2.24$, $p < .05$ found auditory d' given a false alarm to be less than auditory d' given a correct rejection.

Figure 14 shows visual d' by auditory response type. As would be predicted by response interference theories, no significant difference between performance given the two types of auditory response (hit vs false alarm) were found, $F(1,15) = 1.48$, $p > .05$. Also, visual d' given a correct rejection was no different from d' given a miss, $F(1,15) = .40$, $p > .05$. Visual d' given a false alarm was also less than visual d' given a miss, $t(45) = 2.83$, $p < .01$, a finding explained quite well by a response conflict theory that implicated concurrent response-related events in dual-task interference. In addition, the 1200 msec ISI condition produced lower d' scores than the 1600 msec condition,

$F(1,15) = 9.83$, $p < .01$. There was also a significant interaction between speed instructions and type of response (hit vs false alarm), $F(1,15) = 8.0$, $p = .01$, and an interaction, $F(1,15) = 5.18$, $p < .05$, between ISI and type of response (correct rejection vs miss). Tables A6 & A7 (see Appendix) give the beta and reaction time data for this analysis.

Correct versus Incorrect. The hit, false alarm, correct rejection, and miss data from the previous set of analyses were then collapsed into d' , beta, and RT given a correct (hits + correct rejections) versus an incorrect (misses + false alarms) response in the opposite channel. Figure 15 gives auditory d' given a correct versus an incorrect response in the visual channel. There was no effect of visual correctness on auditory d' , $F(1,15) = .51$, $p > .05$, of ISI on auditory d' , $F(1,15) = 1.24$, $p > .05$, or of speed instructions on auditory d' , $F(1,15) = .14$, $p > .05$. There was, however, a significant interaction, $F(1,15) = 4.8$, $p < .05$, between ISI and type of visual response.

The visual data (Figure 16) revealed the same trend as the auditory data, with no effect of auditory correctness, $F(1,15) = .40$, $p > .05$, ISI, $F(1,15) = .003$, $p > .05$, or speed instructions, $F(1,15) = .08$, $p > .05$. There was a significant interaction, $F(1,15) = 4.59$, $p < .05$, between ISI and type of auditory response. Beta and reaction time data for the correct versus incorrect analysis may be found

in the Appendix (Tables A8 & A9).

DISCUSSION

When considered in their entirety, the data from this experiment suggest that capacity was shared between the auditory and the visual task. Further, it was apparent that the major source of shared capacity was that involved in making a response. In the sections that follow, the major results will be summarized, and their relationship to various models of attention discussed.

A limited-capacity system

As discussed earlier, an initial assumption of a model predicting interference during later stages of processing (and of any model other than a resource theory proposing separate pools for all components of the tasks) is that two tasks that overload the total capacity of the system will cause performance decrements. The present experiment demonstrated overall capacity limitations in several ways. First, dual-task performance was not as good as single-task performance, and performance in the more difficult double-stimulation conditions (shorter ISI, instructions emphasizing speed) was worse than that in the easier double-stimulation conditions (longer ISI, no speed instructions).

Second, the performance decrement was expressed in the form of more missed responses, a result predicted by Broadbent's (1958) single channel (limited capacity) model of attention. The two tasks can be performed concurrently at the expense of delayed responses, which translate into misses when a repeated trials procedure with short ISIs is used.

The third and arguably most important piece of evidence supporting generalized capacity limitations were found when the data were analyzed by the latency of the response in the alternate channel (Figures 7 & 8). On trials where the visual RT is greater than the median visual RT (a slow response), auditory d' is low. On trials where the visual RT is less than the median (a fast response), auditory detection performance is high. Visual d' , however, was not dependent on the latency of auditory responses. Since visual RTs were faster overall than auditory RTs in the experiment, it is reasonable to assume that visual responses receive priority and that responses to the auditory channel must wait until processing in the visual channel is complete to some point. Since the auditory short-term store lasts considerably longer than the visual short-term store this strategy would be more efficient than processing the auditory stimulus first (Darwin, Turvey, & Crowder, 1972). The fast-fading visual information could be processed while the lingering auditory traces waited in storage. The

reaction time data supported the detection data in that reaction time given a short response in the other channel was shorter than reaction time given a long response in the other channel. This pattern of results suggests that there is a limited amount of processing capacity available for the two tasks on any given trial, and that as more capacity is demanded by one task less capacity is available to the other task.

While the picture so far does not specify the locus of capacity limitations, it does rule out the notion that all components of the two shared tasks draw on separate capacity stores. Although not a surprising revelation, it is an important one. If this were the case then no reciprocity would have been observed between performance in one channel and the latency of a response in another. The next set of analyses were designed to localize sources of the processing decrements since the aformentioned assumption of the existence of shared capacity has been met.

Response interference

The present set of results provides strong evidence for a response interference/response competition explanation of the observed dual-task decrements. This explanation relies on the primary assumption that capacity is shared within the system (an assumption already supported by data found in the experiment) and asserts that the limitations manifest themselves during the response stage of processing.

First, the effects of a target (a change) in a channel on d' in the other channel were examined (Figures 9 & 10). It was found that, for the auditory channel, d' was lower if a change occurred in the visual channel. These results are consistent with those reported by Sorkin et al. (1973), Sorkin et al. (1976), and Pohlmann & Sorkin (1976). At this point in the analysis the components of the events in the other channel comprising a "change" trial include: a perceptual signal (a visual stimulus that is either red or blue), an internal translation signal linked to a response, and possibly a response. Consequently, this analysis does not by itself distinguish to what degree each of the three components is responsible for the decreased auditory d' . Further breakdown of the data is necessary to support theories localizing interference to a particular stage of processing.

Next, performance in a channel given a response (hit or false alarm) was compared to performance given a non-response (correct rejection or miss) in the other channel (Figures 11 & 12). Again, for the auditory channel, it was found that d' performance was worse when a response was made in the visual channel. This breakdown of the data collapses over the perceptual nature of the event occurring in the other channel (signal, non-signal), and lends support to the hypothesis that dual-task decrements are due to a shortage of resources at the response stage of processing.

The final analysis compared performance within the response vs no response groups (Figures 13 & 14). Once again the reader is encouraged to refer back to Table 1. Within the response group of events, there are responses to signals and responses to non-signals. If response processes are in fact the cause of interference in divided attention, the perceptual nature of the event should not matter and d' in a channel should be the same regardless of whether the concurrent event in the other channel was a hit (response to a signal) or a false alarm (response to a non-signal). Similarly, within the no response group, there are misses (non-response to a signal) and correct rejections (non-response to a non-signal). A response interference theory would predict no differences between the two trial types in the non-response group, while a perceptual interference theory would predict better performance for trial types where there are no signal events occurring in the other channel (false alarms and correct rejections). The analyses on the data broken down by the four trial types did not reveal any differences between hits and false alarms (supported by both auditory and visual data) or between correct rejections and misses (supported by only the visual data). Further, the auditory data showed d' given a visual false alarm to be less than d' given a correct rejection, while visual d' given a false alarm was less than d' given a miss. The auditory reaction time data supported a response

competition interpretation in an analysis where auditory RT given a visual miss was faster than RT given a visual hit. The only finding supportive of perceptual interference was that auditory d' given a visual correct rejection was greater than d' given a miss. A response competition theory would have predicted equal d' 's for trials with a correct rejection or a miss occurring in the other channel.

The findings of increasingly better detection as the event in the opposite channel range from hit to false alarm to miss to correct rejection have been widespread (Eijkman & Vendrik, 1965; Pohlmann & Sorkin, 1976; Moray et al., 1976; and Sorkin & Pohlmann, 1973). The only difference between the current findings and those found in the majority of the literature is that in the current experiment auditory d' given a miss was less than d' given a correct rejection (consistent with the literature) and visual d' given a miss was equal to d' given a correct rejection (inconsistent). Perhaps this minor controversy could be explained by the observed preference for the visual channel, which will be discussed next.

Visual dominance

The result of better performance in the visual over the auditory channel replicates the results from the previous experiment (Casper and Kantowitz, 1985) suggesting visual dominance (Posner, Nissen, & Klein, 1976). Similar results have recently been found by Klapp, Hill, Tyler, Martin,

Jagacinski, & Jones (1985) using a rhythmic monitoring task. In addition to better visual performance overall, the asymmetrical cross-channel effects (Figures 7 through 12) suggest that subjects gave priority to the events occurring in the visual channel. Visual performance remained constant (at a high level) regardless of the type of event occurring in the auditory channel, be it a signal to respond, response, or long RT. Although the total number of visual and auditory signals were equal, there remains one possible explanation for the observed visual dominance effect. The intensities of the auditory and visual stimuli were not equal (see method section for a complete explanation). Since the intensities of the auditory stimuli were equated, the visual task could have been a much easier discrimination task than the auditory task. But if this was the case, it should not have been necessary for auditory task performance to be sacrificed in order to maintain good performance on the visual task. If the visual task was so much easier to begin with it would seem that there would be spare processing capacity remaining (from the visual task) that could be used to improve performance on the auditory task. An experiment presently in progress which (due to improved equipment) was able to equate the visual as well as auditory intensities, should help provide answers to these questions.

The present data are supported by a number of previous studies, some of which have already been mentioned.

However, many other studies have come to slightly different, although not entirely opposite conclusions about bimodal divided attention. Triesman & Davies (1973) found evidence for what they believed to be "modality-specific perceptual capacity". This would entail separate perceptual processing capacity for each modality, minimizing perceptual interference between simultaneous inputs to different modalities. Dual-task combinations using the same modalities for input or the same modalities for output will show greater interference than tasks assigned to different modalities. Results in accordance with Triesman & Davies' have been reported by McLeod (1977), Martin (1980), and Wickens (1980). The results of the present experiment would not be difficult to account for in the light of their findings since each task used a separate modality for input, and a common modality for output. A truer test of perceptual versus response interference might use the same modality for inputs and the same modality for outputs, or further segregate the two tasks by employing different modalities for output. The latter manipulation should result in completely independent processing if indeed the decrements are due to executing two responses in the same modality. The modality-specific perceptual capacity explanation does not explain, however, the results of no perceptual interference from signal detection experiments where subjects monitored two different auditory frequencies.

for targets (Sorkin et al., 1973,; Sorkin et al., 1976). Such experiments have found detectability to be equivalent whether the two frequencies are presented dichotically or monaurally, indicating that physical separation of the two tasks is not necessary for divided attention to proceed uninterfered. Perhaps the question can be reduced to one of the grain of analysis where the definition of a "modality" is concerned; Sorkin and his associates maintain that stimuli within a critical bandwidth will mask each other while those separated by the correct distance can be monitored simultaneously. Thus in auditory signal detection modalities (or channels) differ not by the physical sensing mechanism employed but by the frequencies they are assigned. As long as the data at each level of inquiry are compatible findings from different methodologies should not have to lead to different conclusions concerning attention.

Several models are capable of explaining these findings. One is a hybrid model proposed by Kantowitz & Knight (1976) where early stages of processing proceed in parallel and later stages must proceed serially. A source of limited capacity is available to all of the stages and capacity that is not used up by the earlier stages may be transferred to the later stages. In conditions of capacity "underload" (easy tasks) the model is indistinguishable from a simple stage model where there are separate sources of capacity for each stage. Increases in task difficulty,

however, result in a processing bottleneck at the response end (the serial end) of the system, causing performance decrements. The model holds potential for ambitious mathematical psychologists attempting to quantify the model's predictions regarding system capacity.

A multiple resource model such as Wickens' (1980) would account for the present data by noting that different input modalities and the same output modalities were used. Such a manipulation would result in response interference, since the same pool of capacity is used for response processing. A multiple resource theory approach to this problem would manipulate the task combinations used in input modalities, output modalities, and central processing codes, among other variables. Supposedly, more perceptual interference would be found when two tasks shared the same input modalities than when they used different modalities. If the hypotheses of Wickens' model are true, it would theoretically be possible to design a dual-task situation where each part of each task draws on a separate capacity store and perfect timesharing would result. Such results have been found (Allport, Antonis & Reynolds, 1972) but several questions remain. Factors such as task priority and task difficulty (Navon & Gopher, 1980) have been shown to play an important part in determining how two tasks are timeshared. In addition, the parsimony of resource theory must be compared to that of other approaches. Some have questioned the

utility of adhering to resource theory when more parsimonious explanations are able to account for and predict performance (Navon, 1984).

In summary, it appears that attention is limited when timesharing two tasks in different modalities, and that processing of a response somehow disrupts performance in the concurrently performed task. The present paradigm is rich with possibilities for other experiments that could further illuminate the structure of the information processing system; there is no doubt that converging operations are needed to solve this complex problem. The picture of attention that will emerge will be most likely a detailed one, with the human depicted as a dynamic information processor. Other factors that have appeared to play an important role in dual- and multi-task timesharing are the payoffs associated with different levels of task performance (Heath, 1977), the order of report of a signal in the different channels (Pohlmann & Sorkin, 1976; Martin, 1980), and the method of presentation of the stimuli (Shiffrin & Grantham, 1974). An experiment currently in progress should further determine the potential advantages or disadvantages of presentation strategies and the temporal relationships between the processing requirements of two timeshared tasks.

Table 1. Predictions of perceptual and response interference models for d' in a channel given the type of response in the other channel.

		KEY

		H = hit M = miss CR = correct rejection FA = false alarm
THEORY		
<hr/>		<hr/>
Response Interference		Perceptual Interference
<hr/>		<hr/>
<u>Predictions</u>		
$d' H = d' FA$		$d' H < d' FA$
$d' M = d' CR$		$d' M < d' CR$
$d' H < d' CR$		$d' H < d' CR$
$d' H < d' M$		$d' H = d' M$
$d' FA < d' CR$		$d' FA = d' CR$
$d' FA < d' M$		$d' FA > d' M$

Table 2. Order of experimental conditions.

Number of trials	Condition	ISI
<hr/>		
	Regular Instructions	
50	Double stimulation	1600
50	Single stimulation	1600
50	Single stimulation	1600
50	Double stimulation	1600
50	Double stimulation	1200
50	Single stimulation	1200
50	Single stimulation	1200
50	Double stimulation	1200
<hr/>		
	Speeded Instructions	
50	Double stimulation	1600
50	Double stimulation	1600
50	Double stimulation	1200
50	Double stimulation	1200

Table 3. Auditory and visual RT means.

	Speed Instructions	ISI	Block	Response	No Response
		---	---	-----	-----
Auditory	Regular	1200	1	415	391
			2	400	369
	Fast	1600	1	549	510
			2	497	475
Visual	Regular	1200	1	255	284
			2	246	306
	Fast	1600	1	336	371
			2	336	335
	Regular	1200	1	396	376
			2	372	371
	Fast	1600	1	482	459
			2	441	432
	Regular	1200	1	269	289
			2	257	278
	Fast	1600	1	319	341
			2	311	316

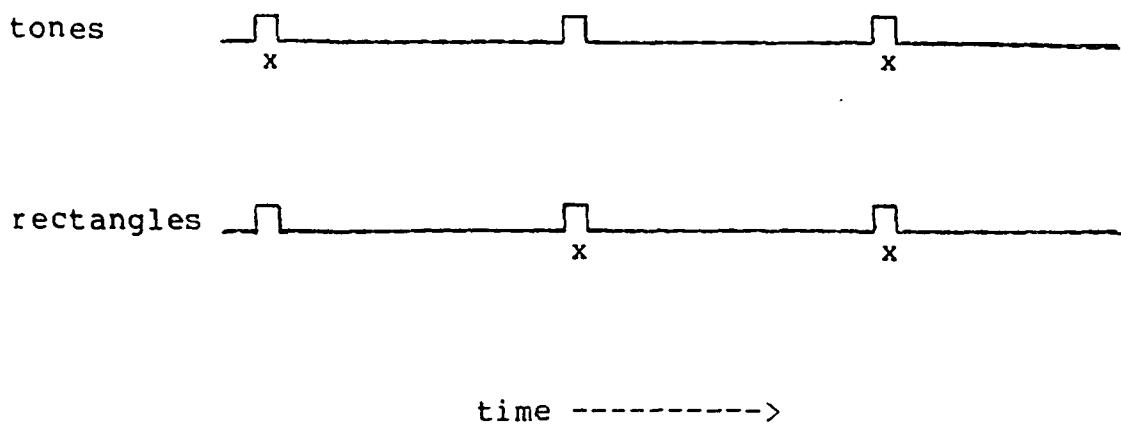


Figure 1. A graphic depiction of a portion of the stimulus sequences used in the experiment. The ISI shown is for the 1600 msec condition, where a pulse indicates a 100 msec stimulus presentation. Note that an "x" under a pulse indicates that a change has occurred on that trial and a response is indicated.

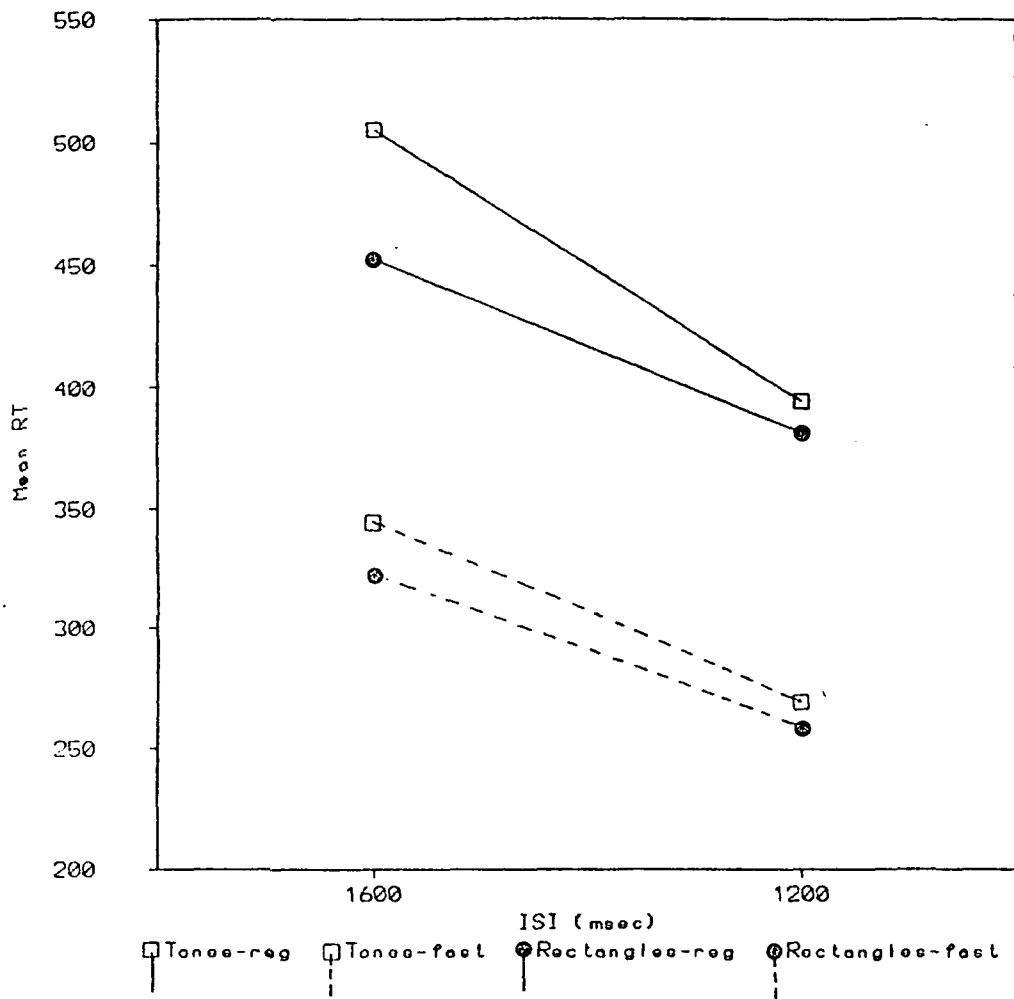


Figure 2. Overall RT as a function of ISI, speed instructions, and modality of stimulus.

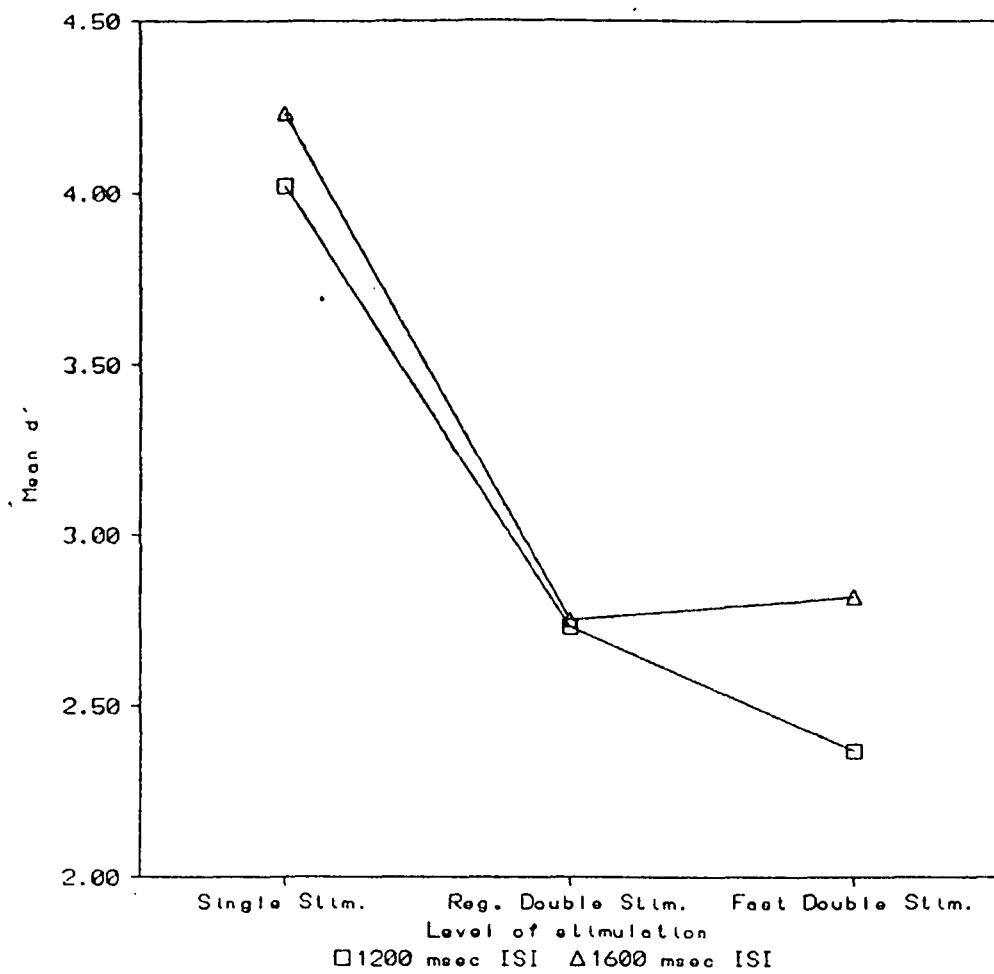


Figure 3. Auditory d' as a function of level of stimulation and ISI.

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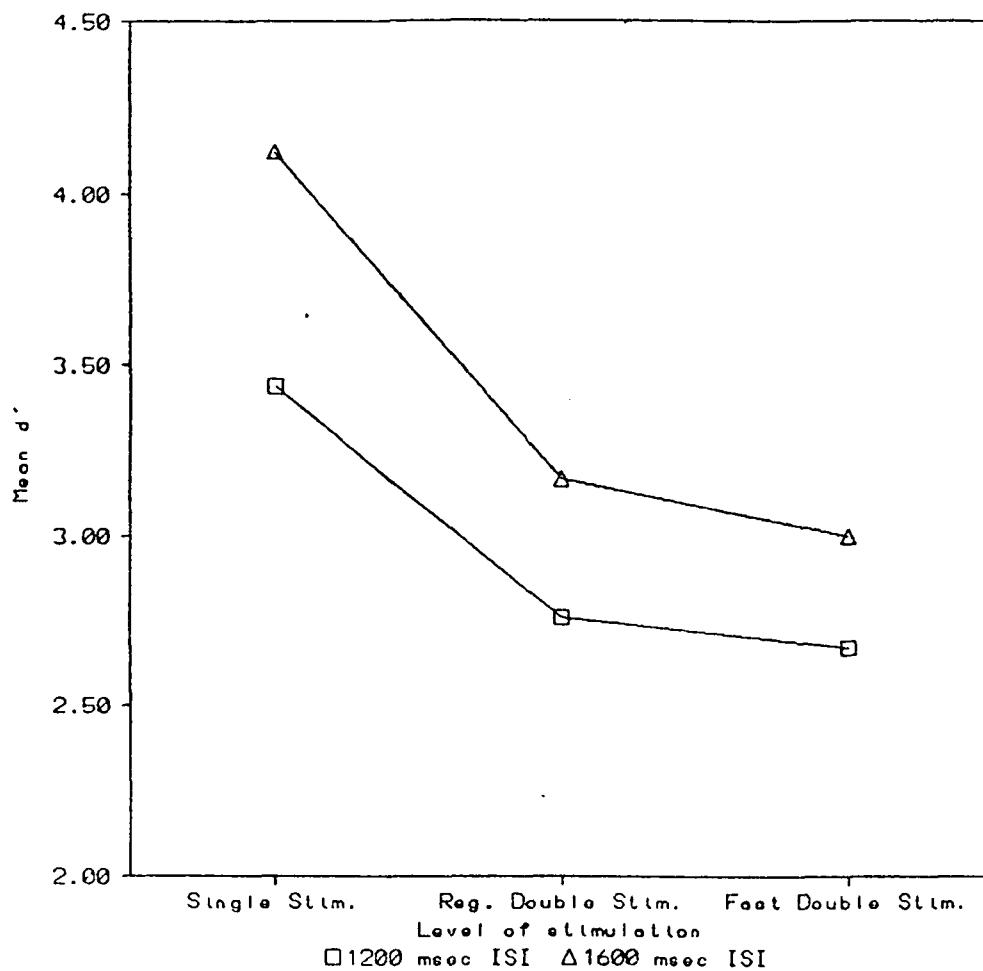


Figure 4. Visual d' as a function of level of stimulation and ISI.

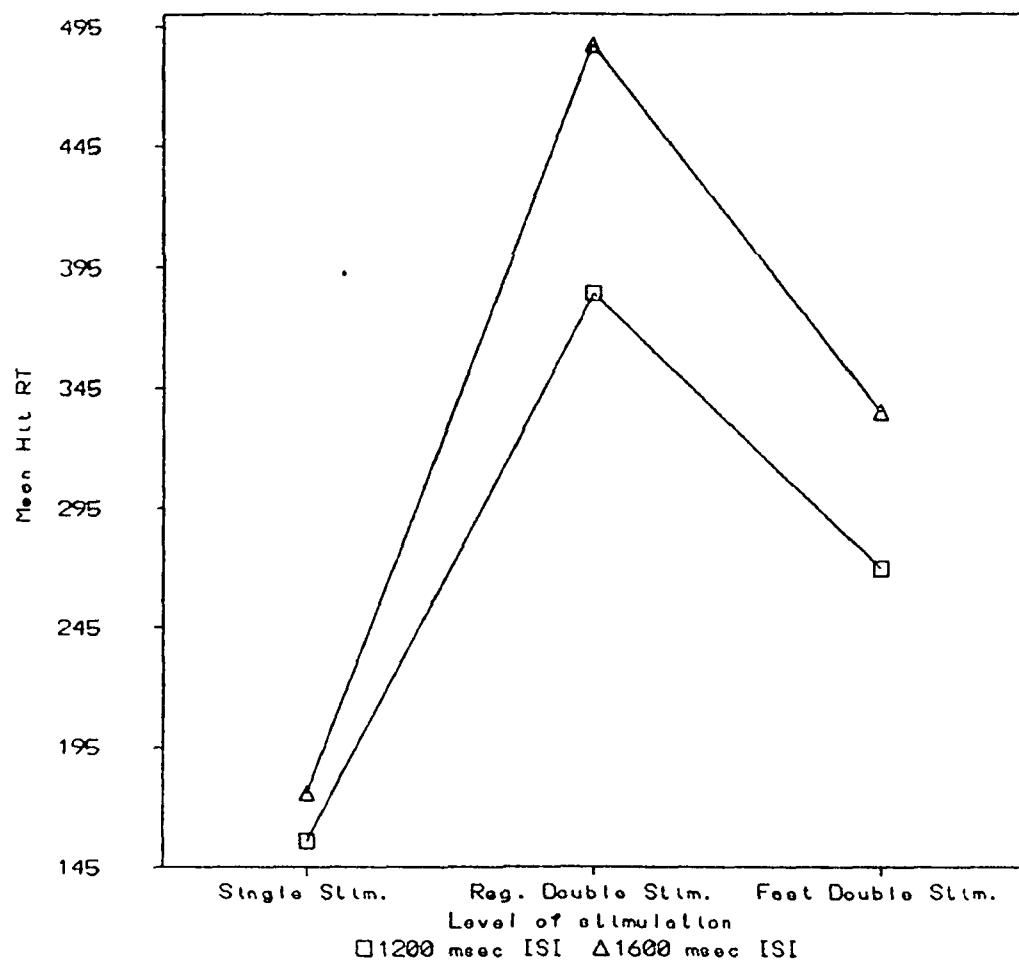


Figure 5. Auditory RT by level of stimulation and ISI.

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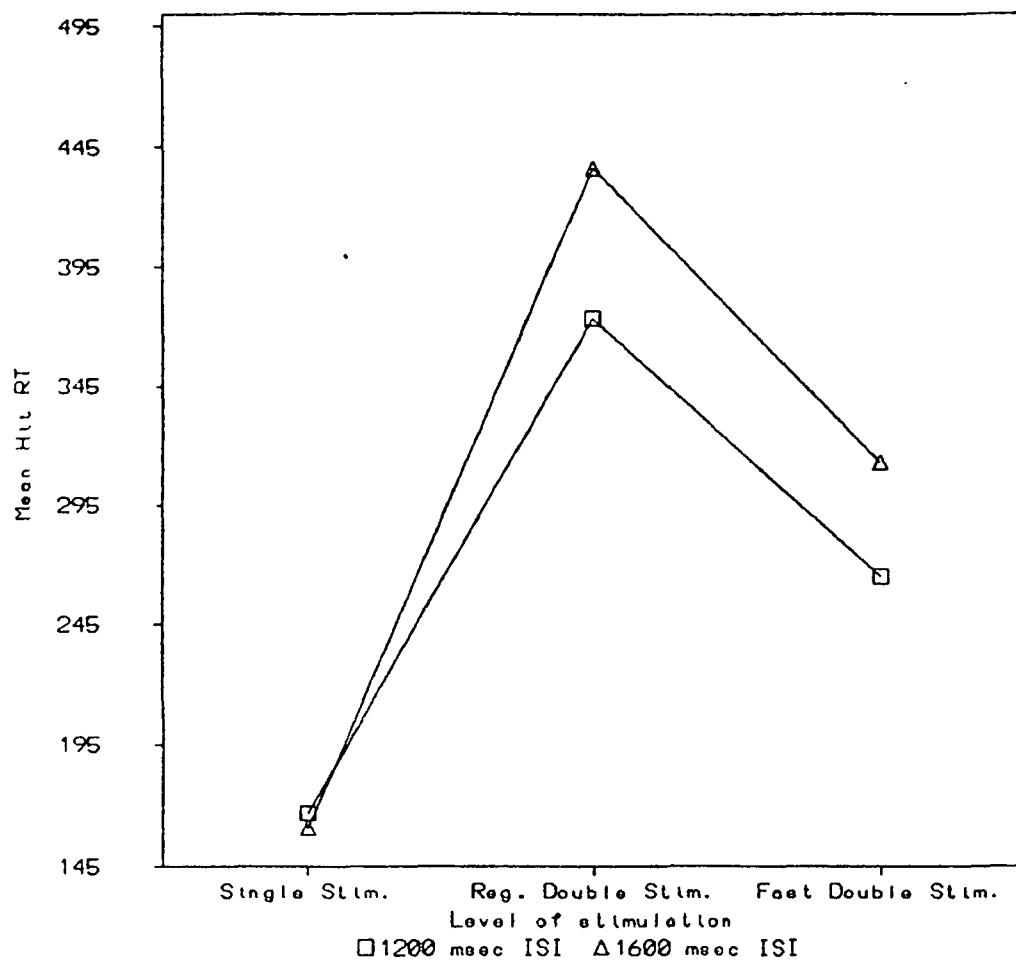


Figure 6. Visual RT by level of stimulation and ISI.

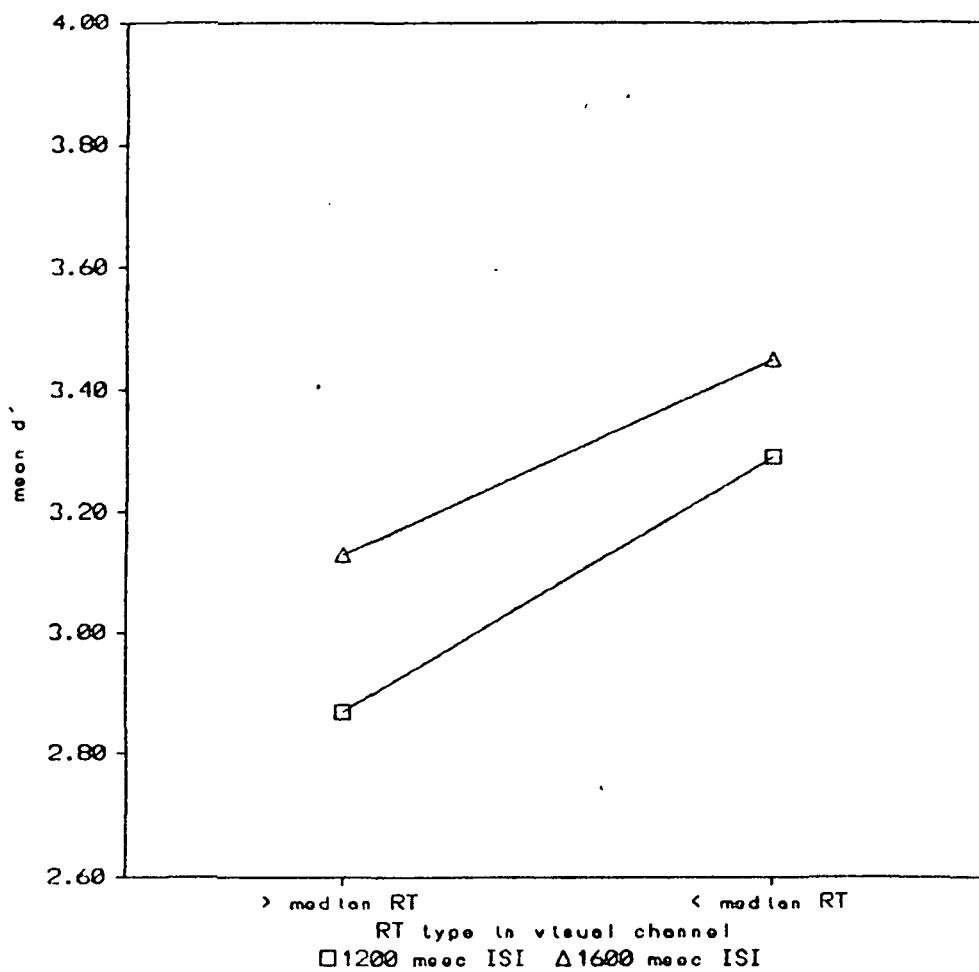


Figure 7. Auditory d' by visual trial type (< median RT, > median RT) and ISI.

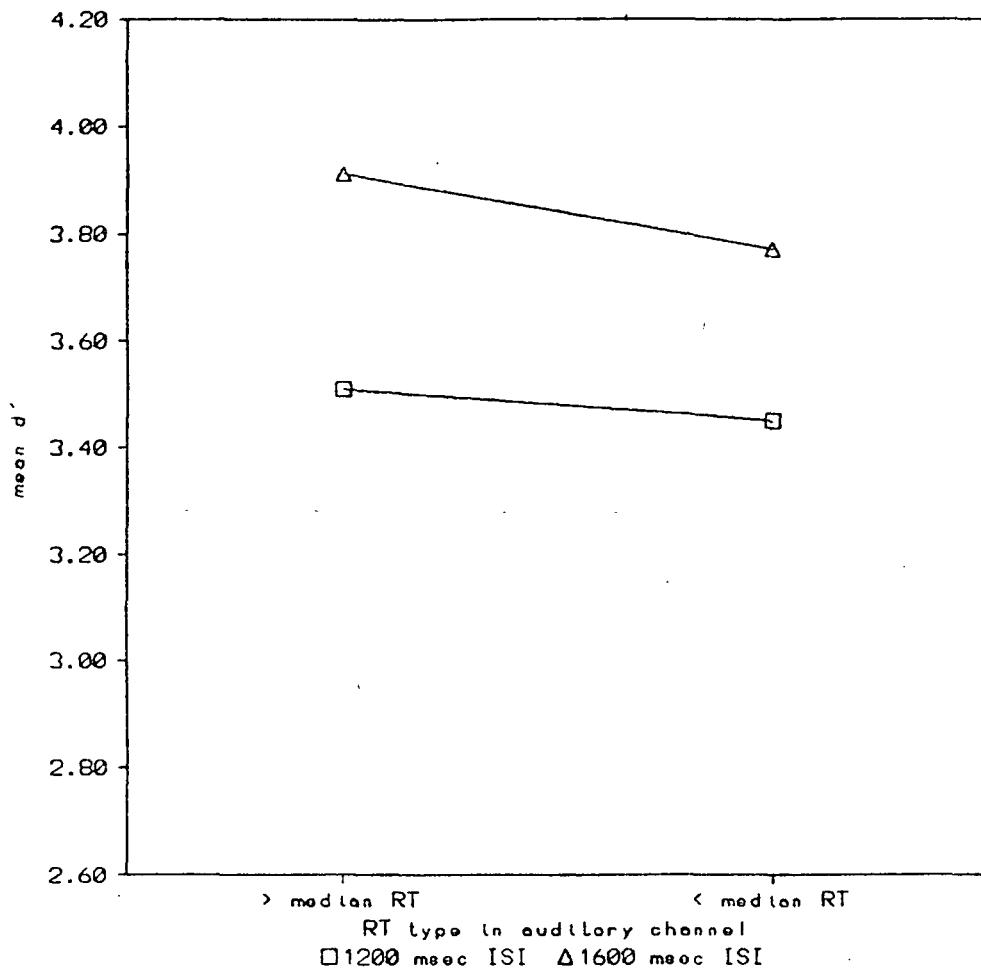


Figure 8. Visual d' by auditory trial type (< median RT, > median RT) and ISI.

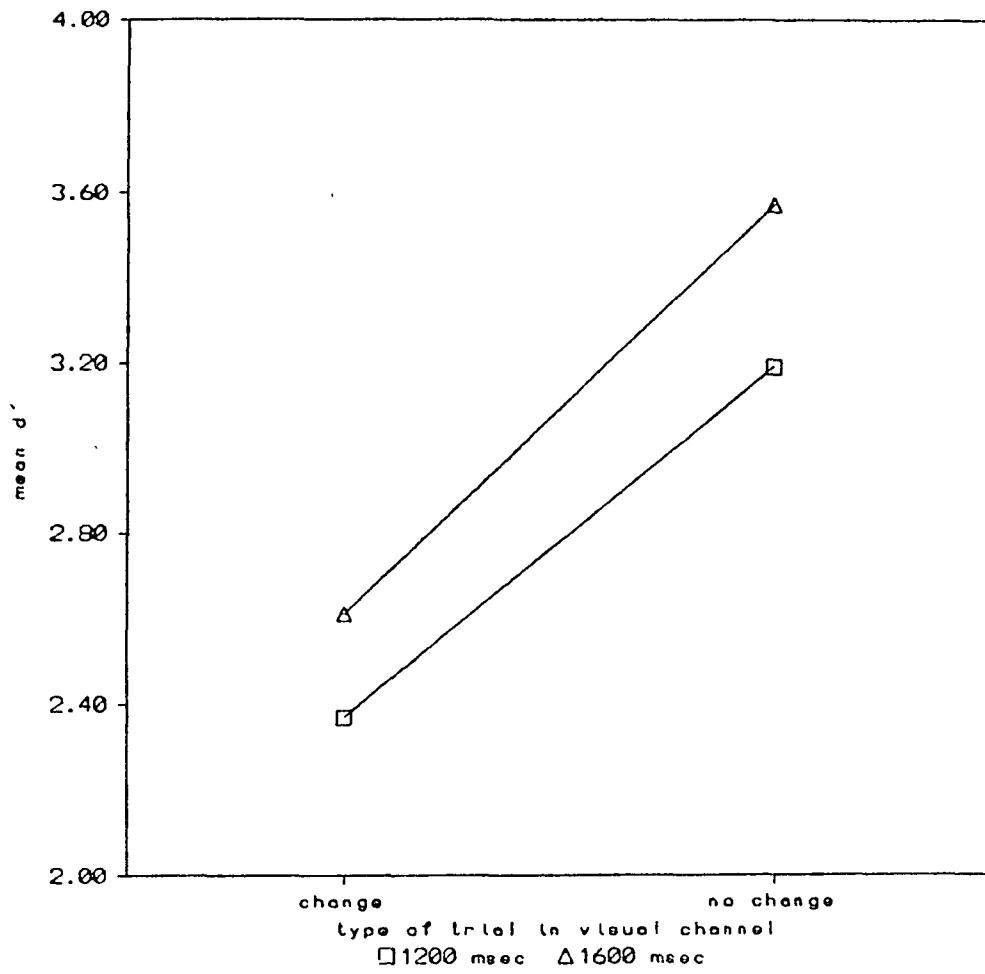


Figure 9. Auditory d' by visual trial type (change, no change) and ISI.

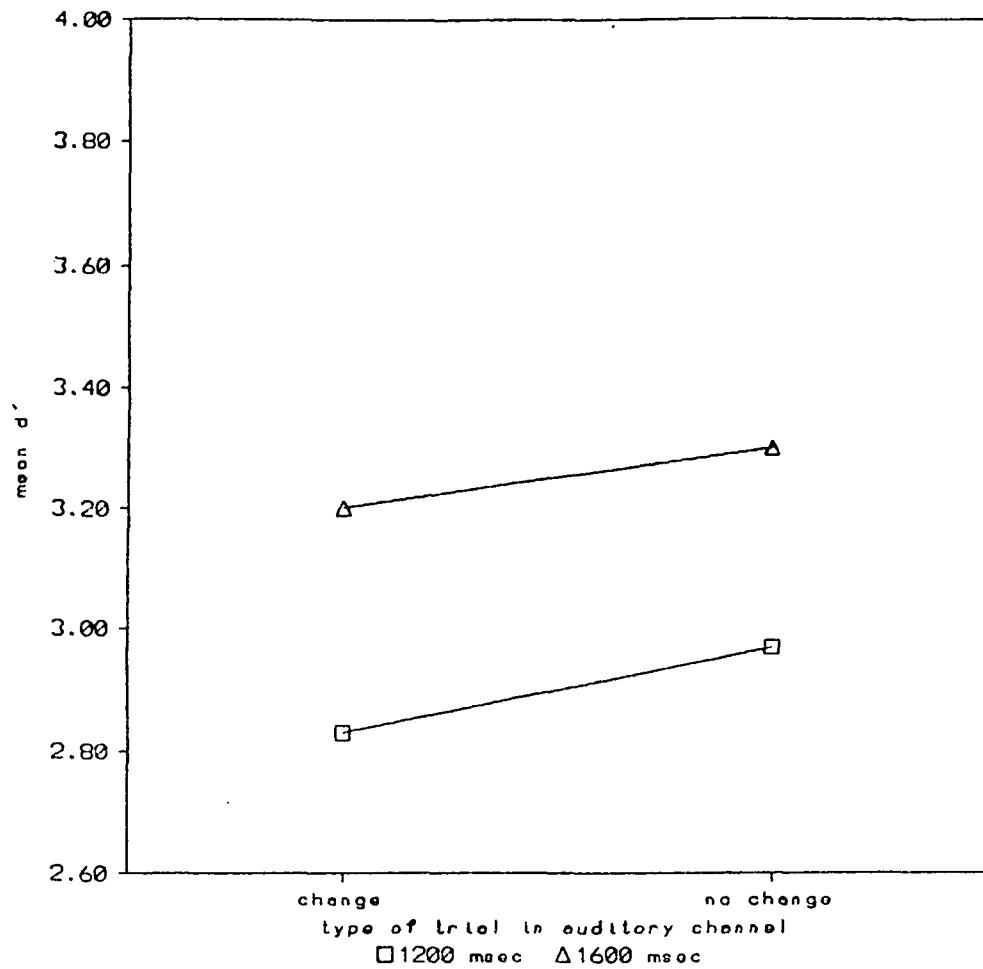


Figure 10. Visual d' by auditory trial type (change, no change) and ISI.

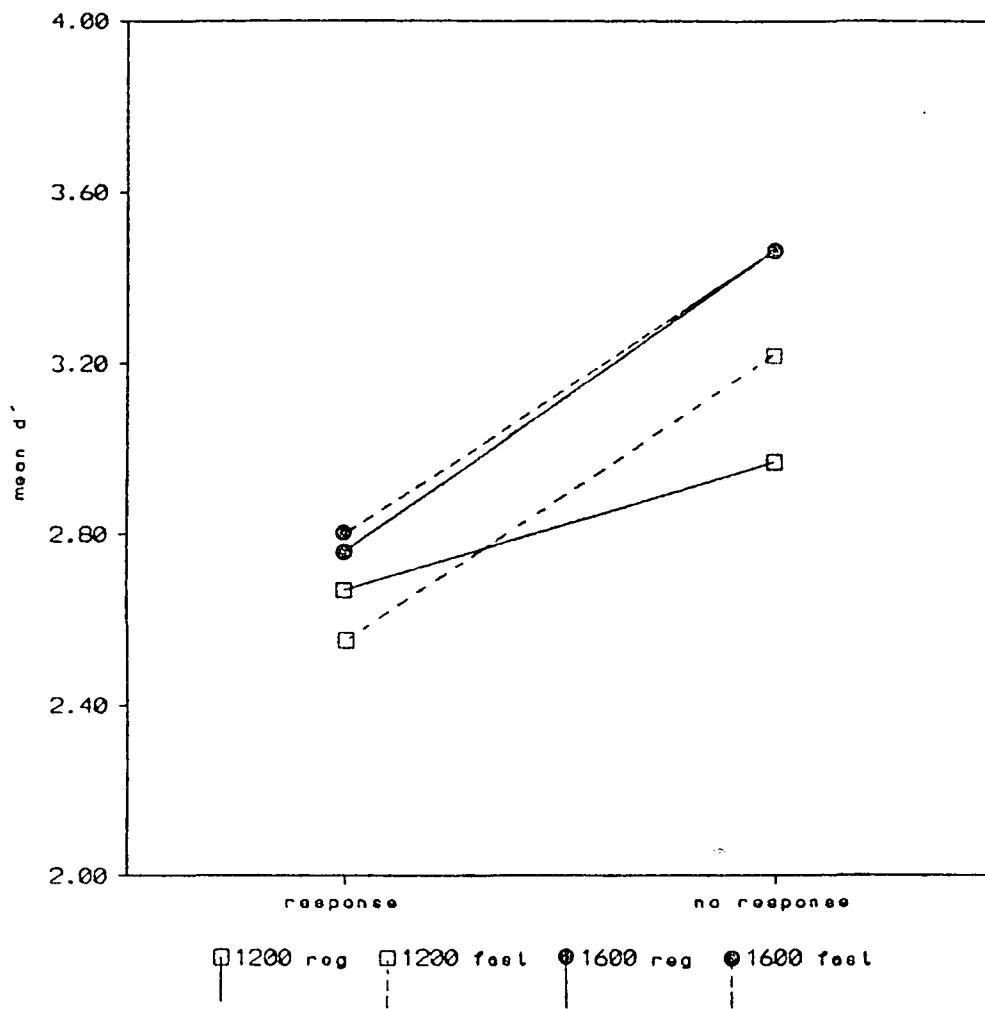


Figure 11. Auditory d' by visual trial type (response, no response), ISI, and speed instructions.

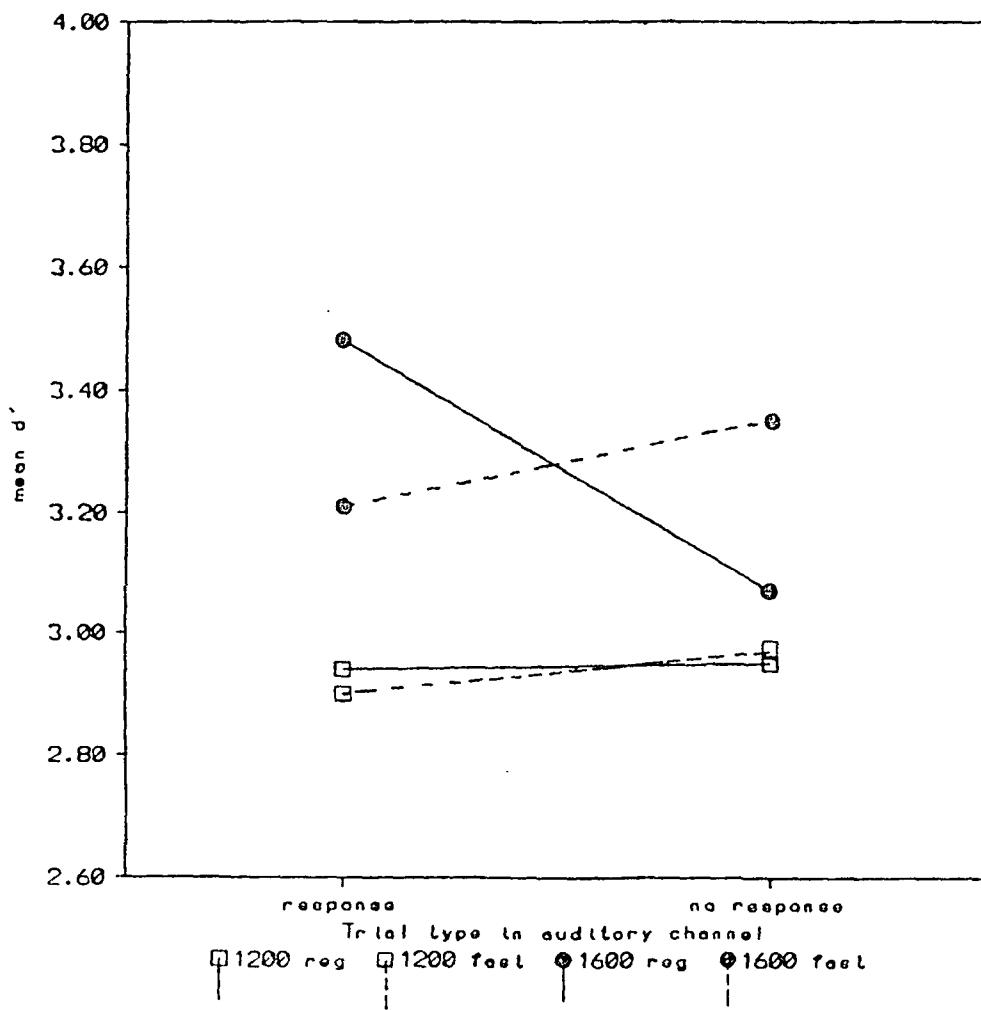


Figure 12. Visual d' by auditory trial type (response, no response), ISI, and speed instructions.

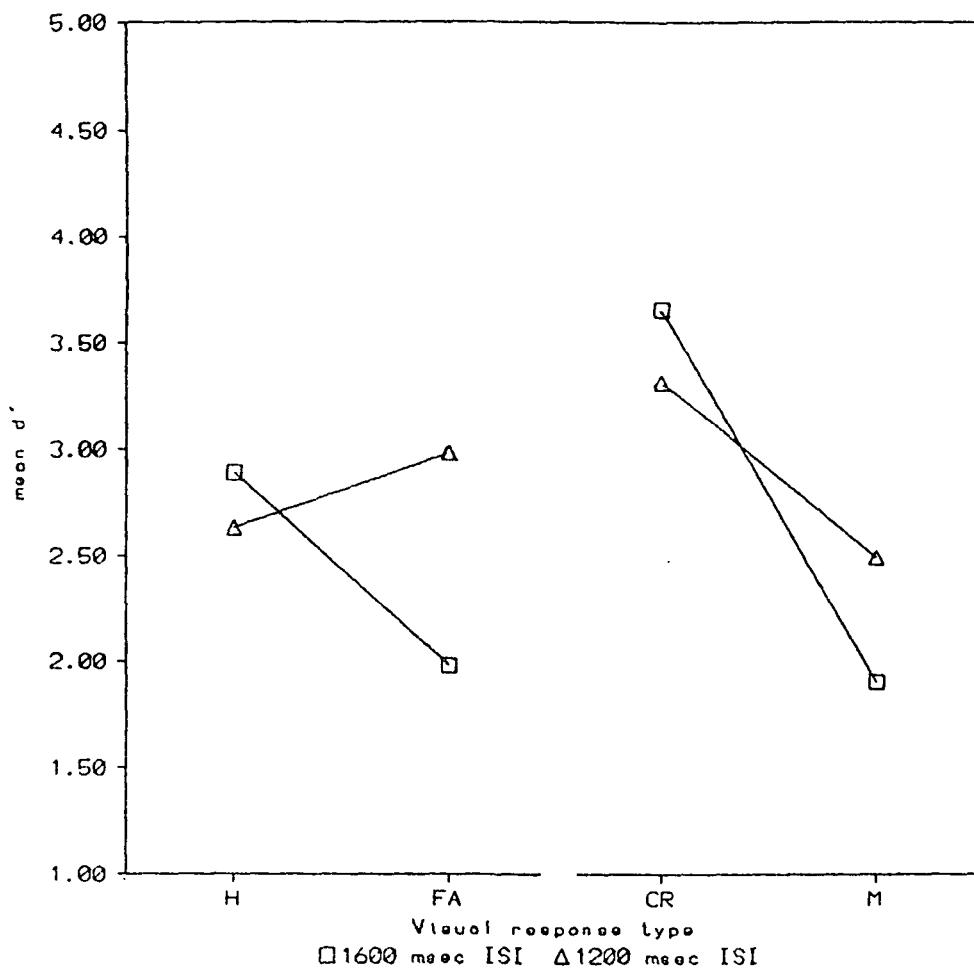


Figure 13. Auditory d' by type of visual response (hit, false alarm, correct rejection and miss) and ISI.

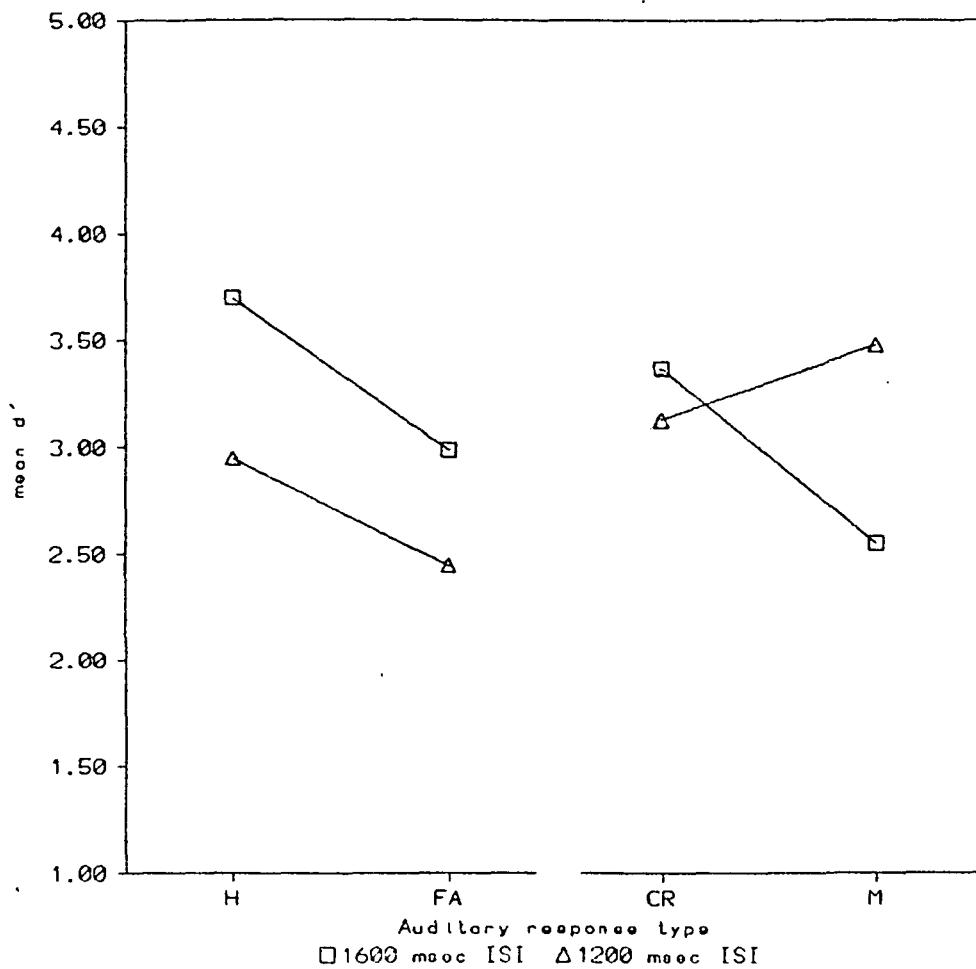


Figure 14. Visual d' by type of auditory response (hit, false alarm, correct rejection and miss) and ISI.

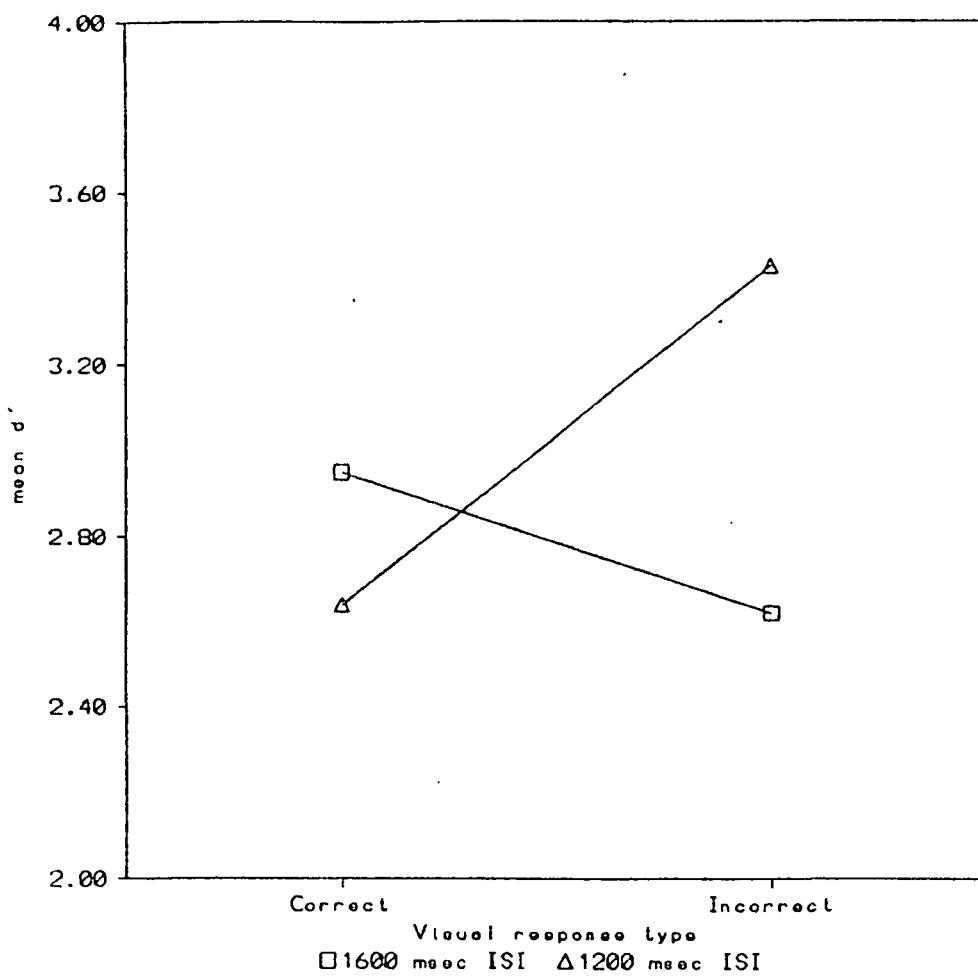


Figure 15. Auditory d' by type of visual response (correct versus incorrect) and ISI.

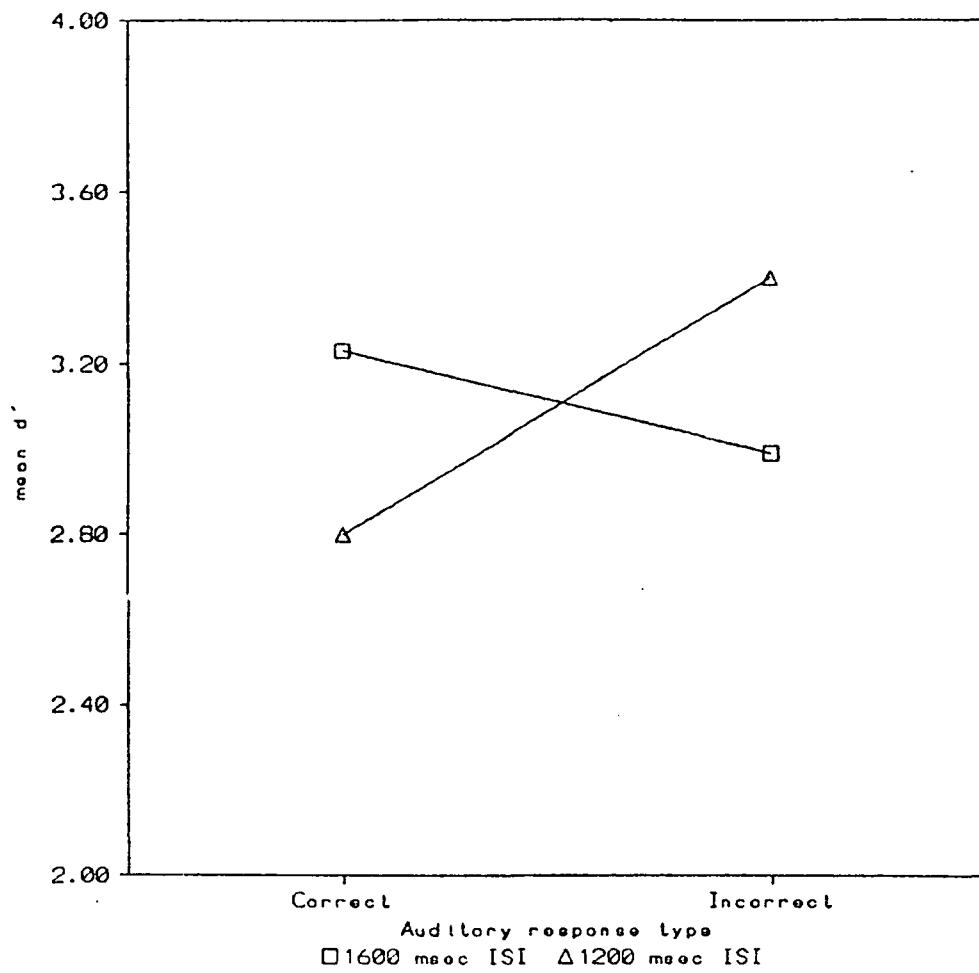


Figure 16. Visual d' by type of auditory response (correct versus incorrect) and ISI.

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APPENDIX

Table A1. Overall error data.

Modality	ISI	Speed Instructions		Regular		Fast	
		1200	1600	1200	1600	1200	1600
	% false alarms	7.9	7.8	11.8	10.8		
Auditory							
	% misses	19.9	15.0	18.7	13.8		
	% false alarms	5.9	5.4	8.4	6.3		
Visual							
	% misses	17.1	13.7	17.9	12.1		

Table A2. Auditory and visual beta scores as a function of the level of stimulation and ISI.

ISI	Single Stimulation	Regular Speed Instructions	Fast Speed Instructions
AUDITORY			
1200	3.60	5.89	2.18
1600	1.38	4.29	1.65
VISUAL			
1200	2.60	4.40	4.84
1600	2.57	7.68	1.61

Table A3. Auditory and visual beta scores as a function of trial type (long RT vs short RT) in the alternate channel.

MODALITY	TRIAL	TYPE
	LONG RT	SHORT RT
AUDIO	7.74	7.25
VISUAL	7.58	7.07

Table A4. Auditory and visual RT as a function of trial type (change vs no change) in the alternate channel.

MODALITY	TRIAL TYPE	
	CHANGE	NO CHANGE
AUDIO	382	376
VISUAL	357	357

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Table A5. Auditory and visual beta scores as a function of trial type (response vs no response) in the alternate channel.

MODALITY	TRIAL TYPE	
	RESPONSE	NO RESPONSE
AUDIO	5.54	6.64
VISUAL	5.77	8.07

Table A6. Auditory and visual beta scores as a function of trial type (H, FA, CR, M) in the alternate channel.

MODALITY	AUDITORY	VISUAL	TRIAL	TYPE	M
			H	FA	
			5.98	1.30	7.37
			5.76	2.37	9.16
					5.68
					6.14

Table A7. Auditory and visual RT as a function of trial type (H, FA, CR, M) in the alternate channel.

MODALITY	TRIAL		TYPE	
	H	FA	CR	M
AUDIO	371	188	368	256
VISUAL	342	220	347	281

Table A8. Auditory and visual beta scores as a function of trial type (correct vs incorrect) in the alternate channel.

MODALITY	TRIAL TYPE	
	CORRECT	INCORRECT
AUDIO	4.26	7.00
VISUAL	4.89	8.59

Table A9. Auditory and visual RT as a function of trial type (correct vs incorrect) in the alternate channel.

MODALITY	TRIAL	TYPE
	CORRECT	INCORRECT
AUDIO	364	326
VISUAL	328	346